A METHODOLOGY FOR PLANNING RECONSTRUCTION ACTIVITIES AFTER A DISASTER CONSIDERING INTERDEPENDENCIES AND PRIORITIES

By

DIANA MERCEDES RODRIGUEZ COCA

Bachelor of Science in Industrial Engineering
Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, Colombia
2000

Master of Science in Industrial Engineering
Universidad de los Andes
Bogotá, Colombia
2006

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2020

A METHODOLOGY FOR PLANNING

RECONSTRUCTION ACTIVITIES AFTER A

DISASTER CONSIDERING INTERDEPENDENCIES

AND PRIORITIES

Dissertation Approved:

Manjunath Kamath Ph.D.

Dissertation Adviser and Chair

Ricki Ingalls Ph.D.

Dissertation Co-Adviser

Balabhaskar Balasundaram Ph.D.

Committee member

Dursun Delen Ph.D.

Committee external-member

ACKNOWLEDGEMENTS

This last 9 years have been the most incredible on my life. A lot of people believed in me and supported me unconditionally. This document is the end of this chapter of my life, and it is the starting point of the next one. Thank you to all of you.

I would like to start by thanking my advisor, Dr. Kamath, who supported and guided me from day one, and my coadvisor, Dr. Ingalls, who, regardless of the distance, always was there for me every time I needed him. Their support allowed me to write the last period on this adventure!

Now, I would like to thank my family. My in-laws who shared in both my happiness and sadness and encouraged me through all this process. Culis my sister-in-law who was my legs, arms, and sometimes my brain (a part of this doctorate is yours). Shifu who was Cristian's support when he needed. My dad who has given me the best example of personal grow that I could have. Anne whose love and kindness have made the most difficult times easier. Marshall who has taught us the value of unconditional friendship.

Finally, Emily my lovely daughter who arrived in my life with the job of healing me and helping me to complete the last step in this research. Jacob, my son, who rescued me from death. My soul mate, Cristian, who did not allow me to give up and who wiped away my tears a million times. Thank you for teaching me the meaning of the word LOVE. Mom who is in heaven and was with me in every step and decision I made. I love you all.

Thank you, God.

Name: DIANA MERCEDES RODRIGUEZ COCA

Date of Degree: MAY 2020

Title of Study: A METHODOLOGY FOR PLANNING RECONSTRUCTION ACTIVITIES AFTER A DISASTER CONSIDERING INTERDEPENDENCIES AND PRIORITIES

Major Field: INDUSTRIAL ENGINEERING

Abstract: A disaster relief chain can be divided into phases such as pre-disaster, disaster response, and post-disaster. This paper focus on the post-disaster phase, specifically in the recovery activity. After a disaster occurs, the road infrastructure gets compromised as roads can be damaged or blocked by debris. This situation represents a threat for the people affected by the disaster because it severely impacts their accessibility to vital locations such as hospitals, police stations, and fire stations. For efficient planning of reconstruction activities, we develop a two-stage methodology employing Steiner Tree and scheduling algorithms that incorporate the principal characteristics of the real-world situation. The objective was to minimize the total completion time to restore access to essential facilities. The mathematical modeling approach identifies the roads that need to be restored considering dynamic resources, priorities, and interdependencies among the essential facilities that need to be connected. In addition, the optimal schedule for restoring the roads, including the crews' assignment is provided. Considering these aspects in the overall methodology were some of the key challenges that our study has addressed. Hazus, a tool developed by the Federal Emergency Management Agency (FEMA) was used to obtain the data related to the impact of a disaster on facilities and transportation network. We replicated the 1994 Northridge Earthquake to test the applicability of our methodology and models under multiple scenarios.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

I. INTRODUCTION

According to the Center for Research on the Epidemiology of Disasters, between 1994 and 2013, natural disasters have resulted in approximately 1.35 million deaths, and 218 million people were affected (Centre for Research on the Epidemiology of Disasters - CRED, 2015). In addition, the 2010 World Disaster Report states that between 2000 and 2010, disasters cost around 987 billion US dollars (International Federation of Red Cross and Red Crescent Societies, 2010). Examples of such disasters are the Asian tsunami (2004), Cyclone Nargis (2008), and Haiti earthquake (2010). Humanitarian logistics is a field that could help reduce the human and economic impact of such disasters.

Thomas and Kopczak (2005) define Humanitarian Logistics as “the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people. The function encompasses a range of activities, including preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance” (Thomas and Kopczak 2005, p. 2). Generally, the vulnerable people are those who have been affected by a disaster. The United Nations defines disaster as “A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources” (United Nations 2009, p. 9). Natural or man-made disasters can develop suddenly or slowly and can be predictable or unpredictable in terms of location and time. Tsunamis, hurricanes, floods, earthquakes, and volcanic eruptions are some examples of natural disasters. On the other hand, terrorist attacks, chemical and nuclear spills, and political disasters are examples of man-made disasters.

The logistics personnel who work in the relief chain activities helping the vulnerable population would like to do so within the least possible time and with the lowest possible cost. A disaster relief chain can be divided into activities or phases. As an example of this classification, Phillips (2005) mentioned mitigation, preparedness, response, and recovery as activities. However, Kovecs and Spens (2007) listed pre-disaster but separated post-disaster into response and reconstruction activities. In another example, Paulsen and Cangelosi (1994) presented preparedness, response, recovery, and evacuation as activities. An explanation of the typical happenings in the disaster phases are given by Altaya and Green (2006).

This dissertation focused on the post-disaster phase, specifically in the recovery activity of a natural or man-made disaster. According to Coppola (2011), recovery is defined as the activity of "returning victims' lives back to a normal state following the impact of disaster consequences" (Coppola 2011, p. 10). For example, after a disaster, the road infrastructure gets compromised. Roads can be damaged or blocked by debris. This situation represents a threat for the people affected by the disaster because it affects their accessibility to vital locations such as hospitals, shelters, police stations, and fire stations. Consequently, there is the necessity of deciding which roads should be restored and the order to do that. The reconstruction order could be affected by restoration and operational interdependencies. Sharkey et al. (2016) mention that "Restoration interdependencies occur whenever a restoration task, process or activity in one infrastructure is impacted by the restoration (or lack thereof) of another infrastructure" (Sharkey et al. 2016, p. 1). In addition, these authors mention that "Operational interdependencies occur when a component of one infrastructure requires services provided by another infrastructure in order to properly function" (Sharkey et al. 2016, p. 2).

The work presented in this dissertation expands the body of knowledge in crew scheduling and routing problems in road restoration topics. In addition, this work could help emergency mangers, government, and communities to make efficient use of reconstruction budgets and resources while serving the affected population. A two-stage methodology employing quantitative models that incorporate the principal characteristics of the real-world situation was developed. The objective of minimizing the reconstruction time is in line with the overarching goal of returning victims' lives "back to normal" as soon as it is possible. The mathematical modeling approach identifies the roads that need to be restored considering dynamic resources, priorities, and interdependencies among the essential facilities that need to be connected. In addition, the optimal schedule for restoring the roads, including the crews' assignment, is provided. Considering these aspects in the overall methodology were some of the key challenges our study has addressed. A case of study was developed using Hazus and Google Maps as sources of information. Hazus a tool developed by the Federal Emergency Management Agency (FEMA) allowed us to replicate the impact of the 1994 Northridge California Earthquake. It provided data related to the location of the essential facilities and the impact on the road infrastructure network for the area of interest. Google Maps was used to calculate the distances among the essential facilities. This case of study allowed us to test the applicability of our methodology and models under multiple scenarios.

The remainder of this dissertation is structured as follows. In Section 2, the motivation for solving this problem is provided. Section 3 contains a brief literature review of the application of quantitative models in humanitarian logistics. Section 4 outlines the research objectives, technical challenges, and goals of this research. Section 5 presents the methodology and associated optimization model using an illustrative example. Section 6 explains the generation of case study data using Hazus and the numerical studies conducted. Finally, Section 7 presents a summary of research contributions, and future work.

II. MOTIVATION

In 2017, the International Disaster Database (EM-DAT) reported that 12,665 natural disasters occurred between 1900 and 2016 around the world. The total impact was calculated as 23 million deaths, 7.6 billion people affected, and US$2.9 trillion in economic damage. Asia is the continent that has suffered the most loss. Europe is in second position in the number of deaths, while Americas have the second highest values in number of events and total economic damage. Africa and Oceania are in fourth and fifth positions respectively (see Table 1).

Table 1. Natural disasters worldwide (1900 – 2016). Source: EM-DAT

Continent	**Events count**	**Total deaths**	**Total affected**	**Total damage ('000 US$)**
Africa	1,742	926,604	510,323,792	$32,369,507
Americas	3,326	752,636	309,600,919	$1,058,922,415
Asia	5,278	19,657,090	6,748,930,984	$1,346,373,057
Europe	1,693	1,658,637	49,354,473	$377,060,847
Oceania	626	12,158	24,806,038	$84,092,508
Total	12,665	23,007,125	7,643,016,206	$2,898,818,334

De Groeve, Vernaccini, and Poljansek (2016) developed the Index For Risk Management (INFORM). The calculation of the index is done using the hazard, vulnerability, and coping capacity aspects of each country. The hazard aspect includes the physical exposure and physical vulnerability features. The socio-economic system is considered in the vulnerability aspect. In addition, the lack of resilience to cope and recover is measured in the coping capacity aspect. Figure 1 shows the INFORM 2017 risk index around the world.

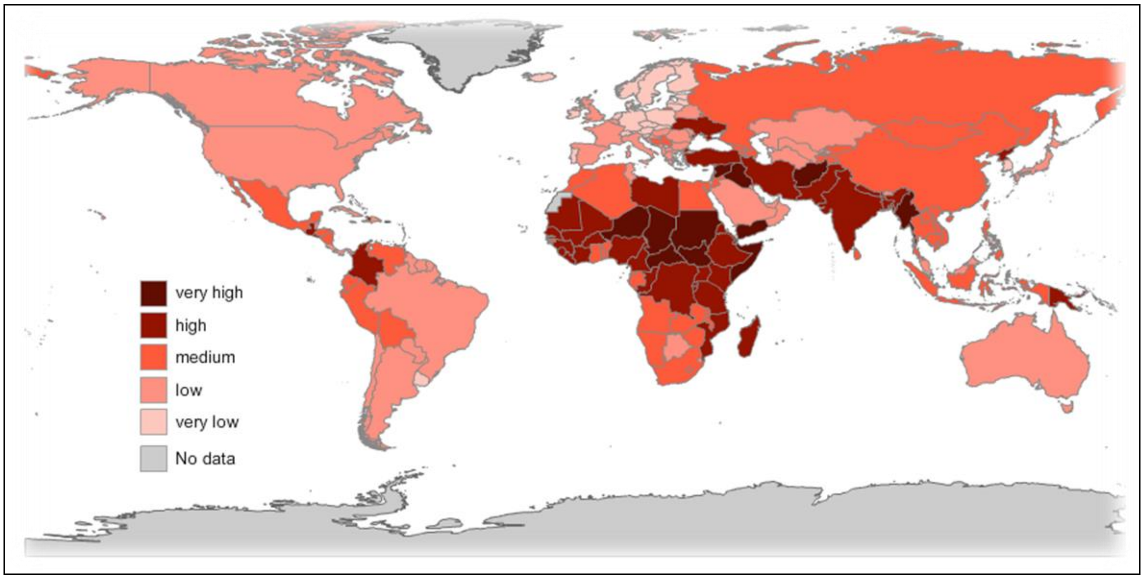


Figure 1. Worldwide INFORM Risk Index.
Source: European Commission, Inter-Agency Standing Committee (IASC). INFORM - Index for Risk Management. http://www.inform-index.org/

As it can be seen in Figure 1, in North and South America, three countries have a high INFORM risk index: Guatemala (5.5), Colombia (5.4), and El Salvador (5.3). While the INFORM risk values are really close in the three countries, it is important to highlight that there is a significant difference in the hazard aspect. Colombia is the country with the highest hazard value (6.8), followed by El Salvador (6.6), and, finally Guatemala (6). The World Bank estimates that in Colombia, 86% of the population is exposed to seismic risk, 28% to floods, and 31% to mass movements (Campos et al., 2012). Colombia has faced 168 natural disasters resulting in 33,790 deaths, 18 million people affected, and US$7 billion in economic damages between 1900 and 2016 (Guha-Sapir et al., 2017).

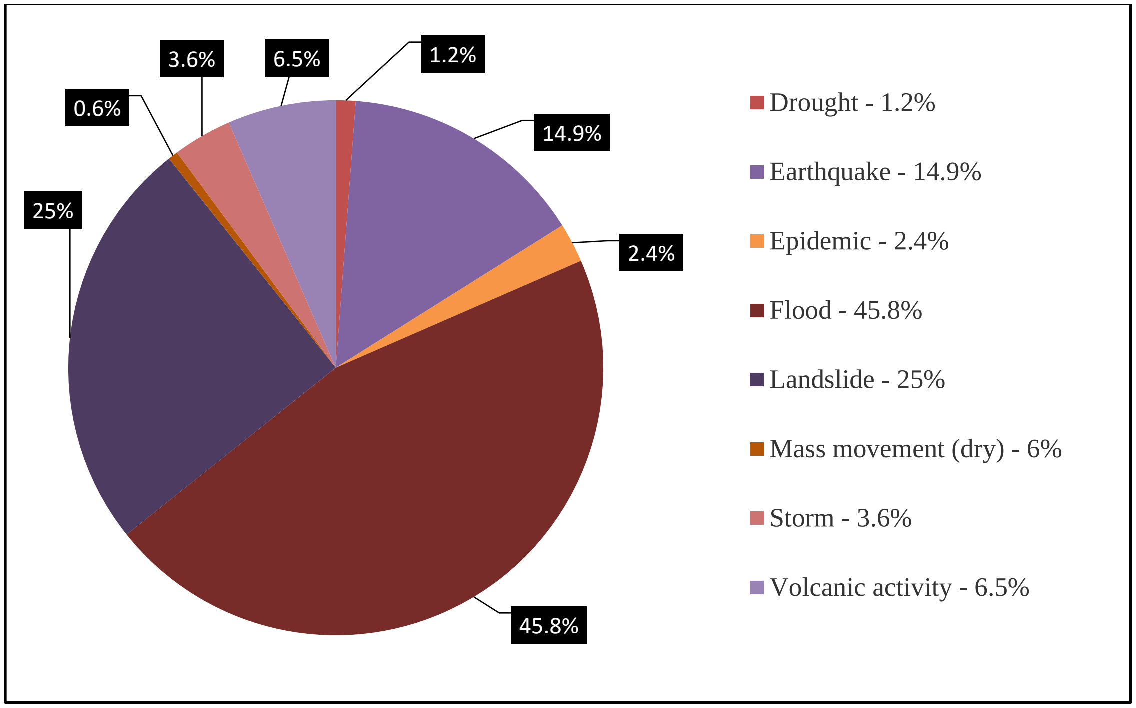


Figure 2. Natural disasters events in Colombia from 1900 to 2016. Source: EM-DAT

As it can be seen in Figure 2, floods and landslides are the most frequent natural disasters in Colombia. These two type of natural disasters cause 84% of the road infrastructure damage (Campos et al., 2012) in Colombia. It is important to mention that the rail, air, and waterways transportation infrastructures are also impacted by floods and landslides.

In Colombia, 91% of the annual investment goes to rehabilitation of the roads and 9% to prevention (Invias, 2009). However, between 2010 and 2011, Colombia handled an enormous amount of rain because of the phenomenon La Niña. According to Campos et al. (2012), 1,600 km of road infrastructure was damaged because of that phenomenon. It represents 9.7% of primary roads, 24.7% of tertiary roads, and 0.9% of the graded area. In addition, 90 bridges and 53 road sections were damaged. To overcome the road infrastructure emergency, an investment 11 times the annual budget was required (Ministerio de Transporte, 2011).

In the aftermath of a disaster, the efficient allocation of resources should give high priority to the reconstruction activities. In terms of the road infrastructure, roads can be damaged or blocked by debris because of a disaster. Due to this, the reconstruction activities are associated with cleaning up or rebuilding processes (Brooks, Kar, & Mendonca, 2013). Which roads should be restored and the order in which they should be restored should be the priority of the disaster management team (Nurre, Cavdaroglu, Mitchell, Sharkey, & Wallace, 2012).

The mathematical modeling approach developed in this dissertation, identified the roads that should be restored. In addition, it provided the schedule of the roads and identified the crew that will oversee the restoration process for each road. The schedule considered dynamic resources, priorities, and interdependencies among essential facilities.

III. LITERATURE REVIEW

A literature review on the application of quantitative models in humanitarian logistics is presented in this chapter. With the objective of organizing the major findings of the literature review, we analyzed the relief chain using the concepts of phases, stages, and activities. Figure 3 illustrates the organization of the literature review. Pre-disaster, disaster, and post-disaster are considered as phases. The stages of the three phases are respectively defined as: preparation; response; and evacuation and reconstruction. The activities are related to the topics that the quantitative models address in the humanitarian logistics field. As it can be seen in Figure 3, inventory management, location, and transportation are the most studied activities.

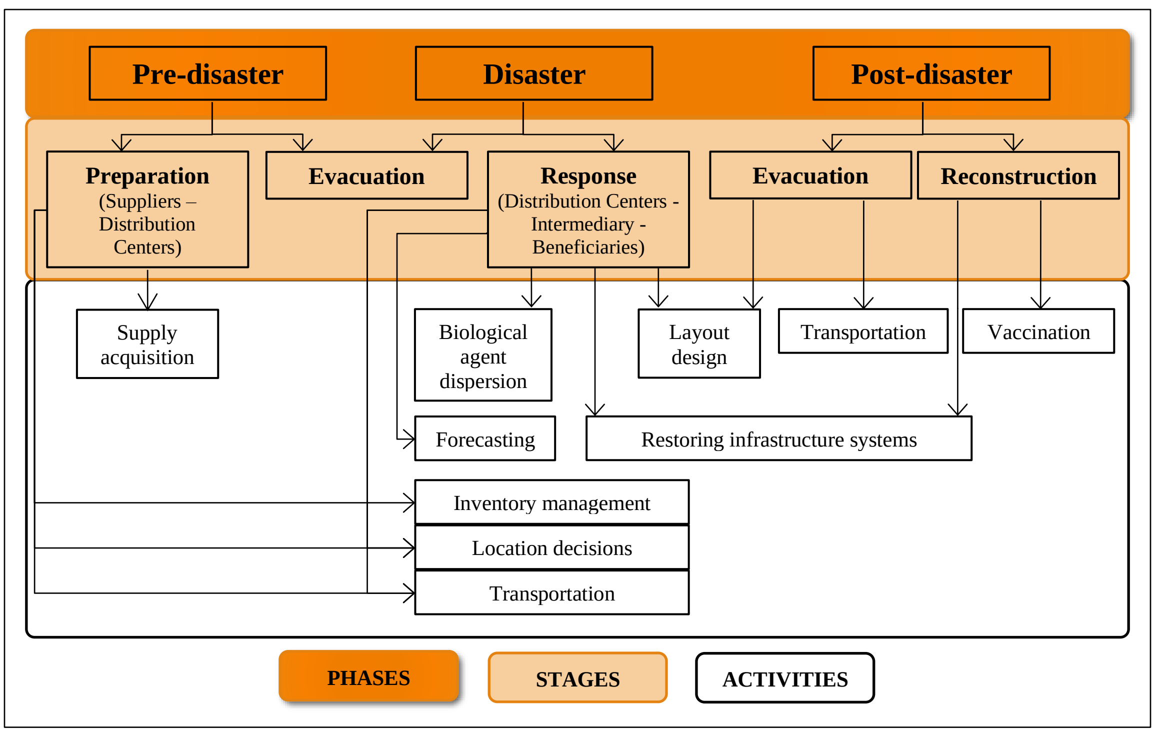


Figure 3. Taxonomy of quantitative model applications in humanitarian logistics

3.1 Pre-disaster phase

In the preparation stage, models address questions such as: How much inventory of essential items do we need to have when a disaster occurs? Where do we need to have those inventories? and, how are we going to deliver them to the distribution centers? Although these are common concerns in the field, there are more questions to address.

In relation with the level of inventory that has to be ready when a disaster could occur, there are some researchers who have developed models to identify the optimal quantities that the logistic personnel need to stock (Ertem, Buyurgan, & Rossetti, 2010; Taskin & Lodree, 2011). However, it is important to highlight that Taskin and Lodree (2011) created the model from a manufacturer's disaster supplies perspective. Hence, the production quantity and the time period when the production needs to be started are the outputs of the model.

Distribution centers are the places where the suppliers deliver the products to be stored until the disaster occurs. A model that helps to choose the best location for the distribution centers and assign demand points to them is presented in Gormez, Koksalan, and Salman F. (2011). Models which link the locations of the distribution centers with the amount of inventory that each should keep in order to respond to a disaster have been developed (B. Balcik & Beamon, 2008; Duran, Gutierrez Marco, & Keskinocak, 2011). After the location of the distribution centers are defined, the next step is identifying the transportation routes that will be used to deliver the products to the stocking points. Ukkusuri and Yushimito (2008) presented a model in which they balance the location and the transportation decisions.

On the other hand, models to evaluate the location of emergency vehicles have been developed by many researchers (Geroliminis, Karlaftis, & Skabardonis, 2009; Iannoni & Morabito, 2007;

Larson, 1974; Marianov & ReVelle, 1996; Silva & Serra, 2007; Takeda, Widmer, & Morabito, 2007). In addition, Larson (1974) balanced the workloads among units. Moreover, Iannoni and Morabito (2007) considered the possibility of “walk in callers” who are customers that approach the emergency services at their base.

The principal decisions in the pre-disaster phase are location, inventory management, and transportation. Nagurney, Yu, and Qiang (2011) addressed all three of them in their work. It is important to highlight that they include details regarding the manufacturing plants which provide the supplies to the distribution centers, and the possible amounts that need to be outsourced. Models which integrate activities of supply acquisition, transportation, and inventory management are presented by Trestrail, Jomon, and Maloni (2009) and Bagchi, Aliyas, and Maloni (2011). Both of those papers discuss delivery of food and the bidding and auction processes for aid procurement.

3.2 Disaster phase

In this phase, the goal is to respond to a disaster. The response activity implies relations among distribution centers, stocking points, and beneficiaries.

Tinguaro Rodriguez, Vitoriano, and Montero (2010) developed a model that forecasts the disaster’s possible consequences such as people killed, injured, homeless, and affected, as well as the monetary loss in US$. These predictions help organizations to determine the resources that they will need to participate in an emergency response process. Knowing that, organizations can take better decisions regarding their participation in the emergency response.

Transportation activity is the most developed in this phase. Models which design the transportation routes among distribution centers, stocking points, and beneficiaries are presented by Adivar and Mert (2010), Ortuño M., Tirado, and Vitoriano (2011), Vitoriano, Ortuño, and Tirado (2011), and Huang, Smilowitz, and Balcik (2012). These authors also include the number of vehicles required on their proposed routes.

Rottkemper, Fischer, and Blecken (2011) presented a model that aids in the management of inventory levels at the stocking points. In addition, it addresses the transportation decision involving the number of trucks or airplanes needed to move the supplies. As a complement, Mohan, Gopalakrishnan, and Mizzi (2011) developed a model to design the layout of the stocking points. In addition, Beamon and Kotleba (2006) designed a model which decides optimal reorder quantities and reorder points.

McCoy and Brandeau (2011) created a model which addresses the decisions of how to split a budget between stocking size and shipping quantities in a relief operation concerning stocking points and beneficiaries. On the other hand, Halper and Raghavan (2011) presented a model that decides the location where a transportable local distribution point needs to be held for different points in time. The distribution of supplies between local distribution points and beneficiaries is the last part of the relief chain in the response level. A model which works in the last mile distribution was developed by Burcu Balcik, Beamon, and Smilowitz (2008).

The integration of location, inventories, and transportation decisions during the disaster phase is addressed by Charles and Lauras (2011) and Tricoire, Graf, and Gutjahr (2012). Charles and Lauras (2011) quantified the supplies that have to be mobilized among distribution centers, stocking points, and local distribution points at a specific time. Additionally, their model calculates the products' stocks to keep at the intermediate points. It also suggests the locations of the distribution centers. In a similar manner, Tricoire et al. (2012) identified the best location for the distribution center. In addition, they calculated the number of times that a vehicle has to travel and the routes that each vehicle needs to follow between local distribution points and beneficiaries. Finally, Tricoire et al. (2012) addressed the possibility that the beneficiaries pick up the supplies themselves from the local distribution points.

An emergency response model to an anthrax attack was presented by Wein, Craft, and Kaplan (2003). The overall model includes an atmospheric dispersion model, a dose response model, a disease progression model, and an intervention model.

The restoration of infrastructure systems combining network design and scheduling problems has been addressed in immediate disaster response by Nurre et al. (2012) and Akbari and Salman (2017). Akbari and Salman (2017) presented a solution method that helps the disaster response management team in deciding the set of closed roads that need to be opened. Also, the authors found which routes need to be used for the vehicles that were in charge of opening the closed roads. The objective is to reach the affected population in the shortest time. In addition, Nurre et al. (2012) developed a model that decides the set of nodes and arcs that need to be fixed to restore a system. They determined the initial allocation of the work groups and their schedule for the repair process. Authors used a weight measure to represent the priorities between the system that is being restored and its customers. Maximizing the cumulative weighted flow is the authors' goal.

3.3 Post-disaster phase

During reconstruction, there are some activities related to health care. Epidemics are common in the post-disaster phase. Gibbons and Subhashish (2009) created a model which allocates people in a vaccine supply network. The model helps to make decisions about the design of the network and creates rules for the delivery of the vaccines inside the network to increase the number of people that can be vaccinated.

Models that address evacuation have been presented by Talebi and Smith (1985), MacGregor Smith (1991), Cruz and MacGregor Smith (2007), Stepanov and Smith (2009), and Ben-Tal, Chung, and Mandala (2011). Ben-Tal et al. (2011) developed models for evacuation traffic flow plans for uncertain demand. In addition, a regional emergency evacuation planning model was presented by Stepanov and Smith (2009). Talebi and Smith (1985) developed an evacuation model for the third floor of a hospital. A building emergency evacuation planning model is proposed by Macgregor Smith (1991) and Cruz and Macgregor Smith (2007).

Road clearance operations models have been developed by Brooks et al. (2013) and Ajam, Akbari, and Salman (2019). The Brooks et al. (2013) model allowed the disaster management team to decide how to distribute vehicles in different paths for debris removal. Additionally, Ajam et al. (2019) presented a model that determined the route for a work troop responsible for clearing blocked roads.

Moreno, Munari, and Alem (2019) developed a model for crew scheduling and routing problem in road restoration. The model’s objective was to minimize the time that affected areas remain inaccessible.

3.4 Pre-disaster and disaster phases

The integration of preparedness and response decisions has been studied by Mete and Zabinsky (2010) and Sanci and Daskin (2019). Mete and Zabinsky (2010) developed a model which discusses where storage facilities should be located, and the inventory levels of medical supplies based off the pre-disaster phase decisions. Additionally, the model can be used to find distribution routes based on the disaster phase decisions. Moreover, Sanci and Daskin (2019) presented a model that decides on the location of restoration equipment for repairing roads prior to the disaster in addition to the location facility locations. The model considers network restoration decisions, such as roads that should be repaired and the number of pieces of restoration equipment used.

3.5 Disaster and post-disaster phases

Ransikarbum and Mason (2016) developed a model that integrates response and early-stage recovery decisions. The authors found a restoration network plan capable of delivering relief supplies to the affected population. The model includes decisions related to the nodes and arcs that need to be restored.

3.6 Pre-disaster, disaster, and post-disaster phases

Manopiniwes and Irohara (2017) presented a model that integrates the three phases of the relief chain. In the pre-disaster phase, the decisions are related to finding the location of the distribution centers (DC) and the amount of relief supplies to store in each of them. In addition, authors assigned the demand points to each DC and designed the transportation plan for the response phase. Finally, an evacuation plan was considered for the post-disaster phase.

Table 2 displays important characteristics of existing studies in the humanitarian logistics area including the categories of phases, stages, solution methods, and practical implementations.

Table 2. Summary of the literature review: quantitative models in humanitarian logistics

No.	Authors	Year	Pre-Disaster	Disaster	Post-Disaster		Solution method	Case study/ implementation
			P	R	E	Re		
1	Larson	1974	✓				Queuing	No
2	Talebi and Smith	1985			✓		Queuing and IP	Third floor of a hospital
3	MacGregor Smith	1991			✓		Queuing	No
4	Marianov and Revelle	1996	✓				Queuing and linear programming	No
5	Wein, et al.	2003		✓			Queuing	No
6	Beamon and Kotleba	2006		✓			Stochastic programming	Kenya and Sudan
7	Iannoni and Morabito	2007	✓				Queuing	No
8	Silva and Serra	2007	✓				Queuing and metaheuristic	No
9	Takeda, et al.	2007	✓				Queuing	Brazil
10	Cruz and MacGregor Smith	2007			✓		Queuing	No
11	Balcik and Beamon	2008	✓				MILP	No
12	Ukkusuri and Yushimito	2008	✓				IP	No
13	Burcu, et al.	2008		✓			MILP	No
14	Geroliminis, et al.	2009	✓				Queuing and heuristic	No
15	Trestrail, et al.	2009	✓				MILP	No
16	Gibbons and Subhashish	2009				✓	Simulation	North American medium density region
17	Stepanov and Smith	2009			✓		Queuing and IP	No
18	Rodríguez, et al.	2010		✓			Decision support – Knowledge based system	No
19	Mustafa, et al.	2010	✓				Simulation	No
20	Adivar and Mert	2010		✓			MILP	Algeria
21	Mete and Zabinsky	2010	✓	✓			MILP	Seattle
22	Taskin and Lodree	2011	✓				Sequential Bayesian decision model	Fictitious storm
23	Gormez, et al.	2011	✓				MILP	Istanbul

No.	Authors	Year	Pre-Disaster P	Disaster R	Post-Disaster E	Re	Solution method	Case study/ implementation
24	Duran, et al.	2011	✓				MILP	Worldwide
25	Nagurney, et al.	2011	✓				The Euler method for the solution of variational inequalities	No
26	Aniruddha, et al.	2011	✓				MILP	No
27	Ortuno, et al.	2011		✓			MILP	Niger
28	Vitoriano, et al.	2011		✓			MILP	Haiti
29	Beate, et al.	2011		✓			LP	Burundi
30	Mohan, et al.	2011		✓			Simulation	Arizona
31	McCoy and Brandeau	2011		✓			Dynamic Programming-Heuristic-Simulation	No
32	Halper and Raghavan	2011		✓			Infinite-Dimensional MIP-Heuristic	No
33	Aurelie and Matthieu	2011		✓			MILP	No
34	Aharon, et al.	2011			✓		LP	No
35	Huang, et al.	2012		✓			MILP and heuristic	No
36	Tricoire, et al.	2012		✓			MILP and heuristic	Senegal
37	Nurre, et al.	2012		✓			IP and heuristic	New Hanover County and North Carolina
38	Brooks, et al.	2013				✓	Queuing	No
39	Ransikarbum and Mason	2016		✓		✓	Goal programming	South Carolina and California
40	Akbari and Salman	2017		✓			MILP and heuristic	Istanbul
41	Manopiniwes and Irohara	2017	✓	✓	✓		Stochastic programming	Thailand
42	Moreno, et al.	2019				✓	Branch-and-Benders-cut	No
43	Sanci and Daskin	2019	✓	✓			Stochastic programming	Istanbul
44	Ajam, et al.	2019				✓	MIP and heuristic	Istanbul and Kartal

M =Mitigation P=Preparation R=Response E=Evacuation Re=Reconstruction

MILP = Mixed integer linear programming IP = integer programming

3.7 Literature review's conclusions

The following studies are directly related to our work. Akbari and Salman (2017) developed models for the disaster phase. Their models identify the set of closed roads that need to be open and the routes for the construction equipment that restore the closed roads. However, they included neither interdependencies nor priorities in their model. Nurre et al. (2012) created a model that identifies: (1) the set of nodes and arcs that need to be fixed in order to restore a system; and (2) the initial allocation of the work groups and their schedule for the repair process during the disaster phase. They used a weighted flow objective function to represent some priorities between the system that is being restored and its customers. Some limitations of the model are that the model did not include interdependencies, and the authors recognized that the road restoration operations may need a different approach than the approach used in other infrastructures such as power distribution. Ransikarbum and Mason (2016) presented a model that integrates response and early-stage recovery decisions. The authors obtained a restoration network plan, which is capable of delivering relief supplies to the affected population. The model includes decisions related to the nodes and arcs that need to be restored. Nevertheless, the model did not provide the sequence in which the restoration needs to be done, did not consider the work crews, and included neither dependencies nor priorities in their model. Moreno et al. (2019) applied their model in the post disaster phase for the crew scheduling and routing problem in road restoration. Again, they do not consider interdependencies or priorities. Additionally, their model only provided the schedule for one crew. Also, Sanci and Daskin (2019) developed a model for the preparedness and disaster phases that considered facility location and restoration network decisions. The focus on their model was on considering uncertainty.

As it can be seen in Table 2, almost all of the authors have applied exact algorithms as solution methods of their models while a small fraction complemented the algorithms with heuristics.

Figure 4 shows that the post-disaster phase has witnessed fewer research studies. In this phase, 6 papers address the evacuation level while only 5 papers address the recovery level. We can conclude that there is a need for additional research in the recovery phase specifically in debris management and restoration of affected road infrastructure.

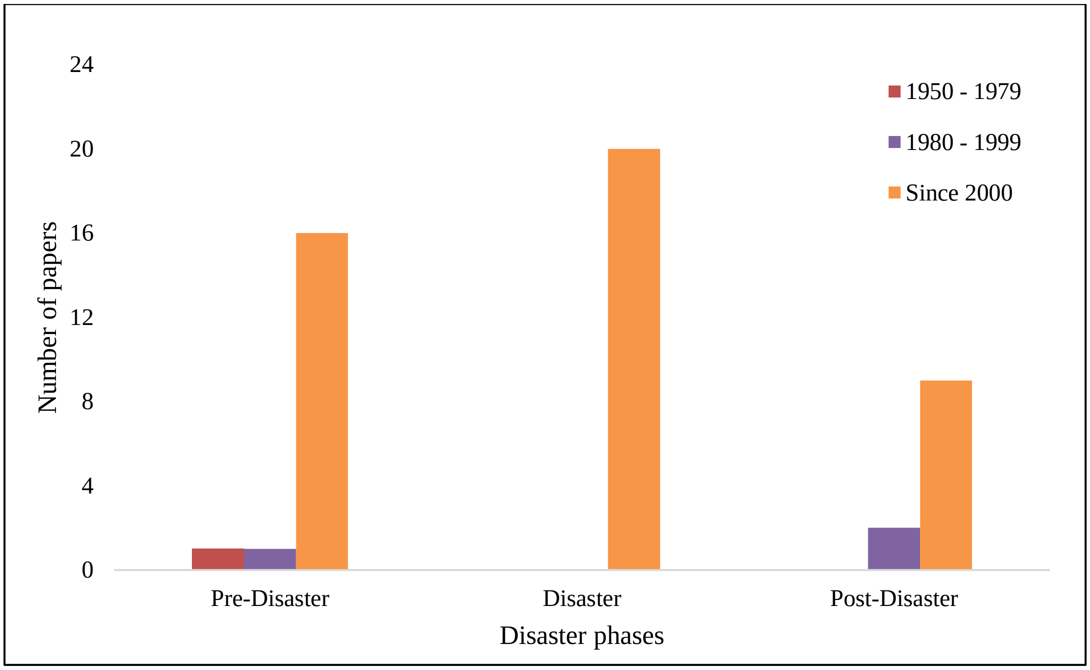


Figure 4. Research contribution by phases

Our conclusion is also reinforced by others, for instance, Matsumaru, Nagami, and Takeya (2012) stated that "research on post-disaster reconstruction is insufficient" (Matsumaru et at. 2012, p.12). In addition, Altay and Green (2006) surveyed articles until 2004 and concluded that more "research is needed for recovery efforts" (Altaya and Green. 2006, p. 483). As a complement of Altay and Green (2006) work, Galindo and Batta (2013) reviewed articles between 2005 and 2010 and the main conclusion was "most trends have remained, e.g., lack of research for recovery activities" (Galindo and Batta. 2013, p. 210). Moreover, Habib, Lee, and Memon (2016) surveyed papers between the years of 2005 and 2015. One of their conclusions was that "research in the mitigation and recovery phase of the HSC, which includes debris management and repair of affected infrastructure, has a very small portion, particularly the long-term recovery after disaster is the most neglected area” (Habib et al. 2016, p. 10).

IV. STATEMENT OF RESEARCH

4.1 Problem description

The main goal of this dissertation was to address a real problem that the emergency management faces during reconstruction activities in post-disaster operations. After a disaster the road infrastructure gets compromised. Roads can be damaged or blocked by debris. This situation represents a threat for the people affected by the disaster because it affects their accessibility to vital locations such as hospitals, shelters, police stations, and fire stations. We need to decide which roads should be restored and the order to do that.

We use a network representation to capture the road infrastructure system. Figure 5 shows an example of a road network before a disaster strikes. In the network, nodes represent facilities such as shelters, hospitals, fire stations, and schools. The arcs represent a physical connection (roads or bridges) between nodes. The solid line indicates that the road is in a normal working condition.

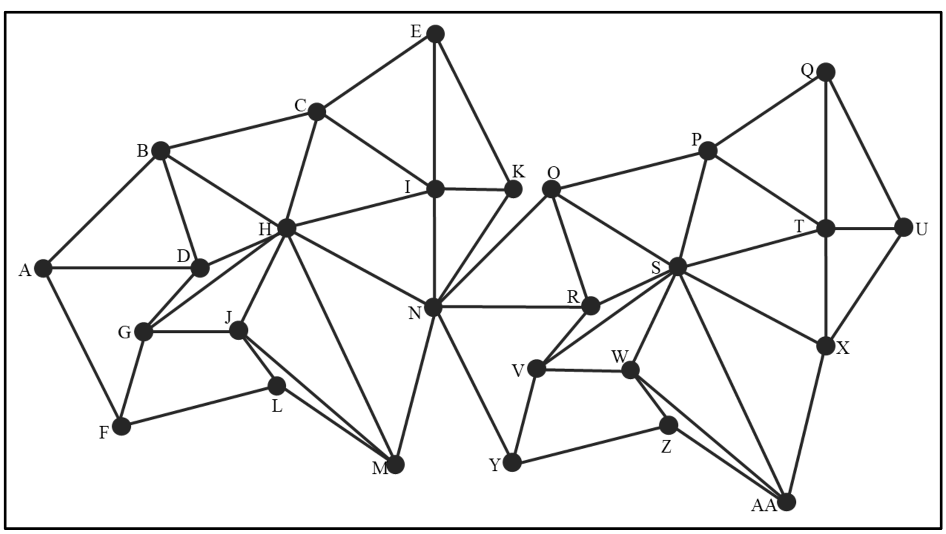


Figure 5. Representation of a road infrastructure system before a disaster

After a disaster occurs, the transportation infrastructure is compromised and some connections (arcs) between facilities (nodes) are broken. Figure 6 is a representation of a road infrastructure system where only three roads (solid lines) are in a working condition.

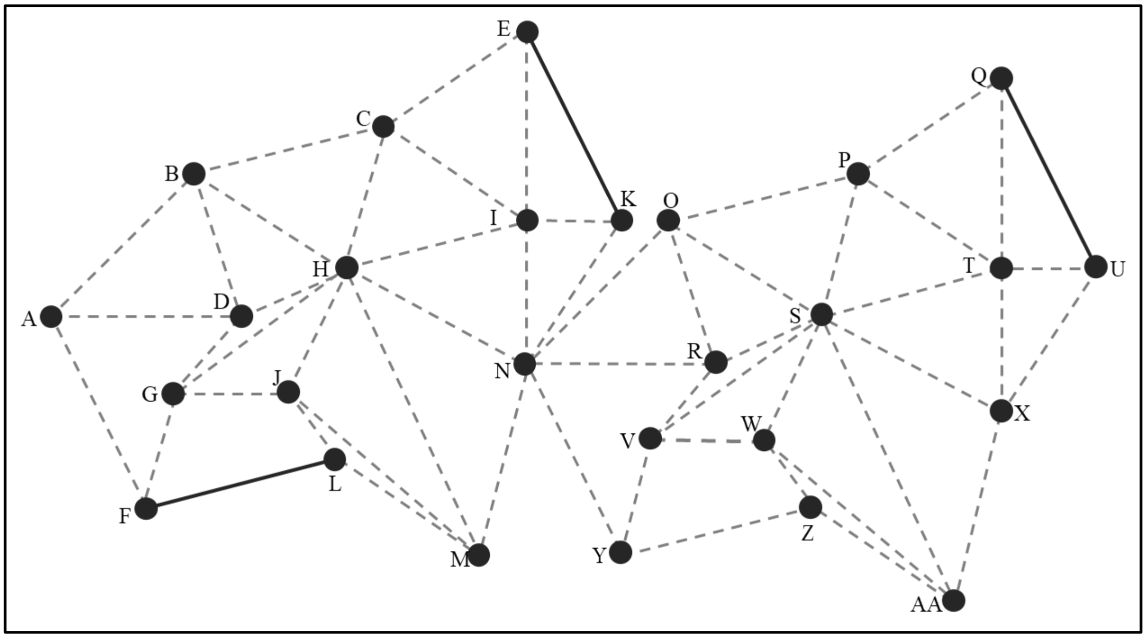


Figure 6. Representation of a road infrastructure system after a disaster

As Hwang, Park, Lee, Lee, and Kim (2015) state, the emergency management team needs to design a plan for facilities and infrastructure to be functional within a limited time with the objective of allowing victims to have access to all the essential places where they could go before the disaster happened. The first part of this plan is repairing the transportation infrastructure. Due to that, it is necessary to identify which roads need to be cleaned up or reconstructed (Akbari & Salman, 2017; Moreno et al., 2019; Nurre et al., 2012; Ransikarbum & Mason, 2016; Sanci & Daskin, 2019) and the sequence in which they are cleaned up and reconstructed (Moreno et al., 2019; Nurre et al., 2012). In addition, it is necessary to identify the crew that will be in charge of restoring the roads (Akbari & Salman, 2017; Nurre et al., 2012). Furthermore, the emergency manager needs to consider some priorities in planning the reconstruction activities (Nurre et al., 2012; Sharkey et al., 2016).

In this dissertation, we developed a methodology and associated mathematical models to provide decision support to the emergency management team in determining how the road infrastructure system should be restored during reconstruction in the post-disaster phase. These mathematical models provide the crews' schedule for the reconstruction activities. The schedule considers dynamic resources, priorities, and interdependencies between facilities. Considering priorities and interdependences simultaneously in determining the crews' schedule for reconstruction activities has not been addressed in the literature as it was discussed in the literature review's conclusions (section 3.7.)

4.2 Technical Challenges

Based on the characteristics of the problem, this dissertation overcame three technical challenges.

Priorities among facilities. The emergency manager needs to consider some priorities in restoring the road infrastructure. After a disaster strikes, facilities such as shelters, hospitals, fire stations, and schools need to be reached by emergency teams and people affected. Access to certain facilities may have to be restored first before considering access to others. It is reasonable to expect that the emergency manager or management team determines the order in which access to facilities should be restored. For instance, access to shelters and hospitals may be more important than access to grocery stores.

In our methodology, we grouped facilities according to the urgency in which they need to become accessible. Each group is assigned a priority, with priority 1 being the highest priority. The quantitative models that we developed are executed iteratively for each priority group. At the end of a priority group iteration, all the facilities within that group must be connected by a set of working roads.

Interdependencies among facilities. Sharkey et al. (2016) mention that "Restoration interdependencies occur whenever a restoration task, process or activity in one infrastructure is impacted by the restoration (or lack thereof) of another infrastructure" (Sharkey et al. 2016, p. 1).

In addition, these authors mention that "Operational interdependencies occur when a component of one infrastructure requires services provided by another infrastructure in order to properly function" (Sharkey et al. 2016, p. 2). Thus, the emergency manager must identify the interdependencies among the facilities for which access needs to be restored. For instance, there is an operational interdependence between a fire station and a water supply plant because the firefighters need water to be able to do their job. We translate this interdependency to a requirement in our models that the fire station and the water supply plant must be accessible in the same priority group. This does not mean that these two facilities are in the same priority group. For instance, let us suppose that the fire station is in the priority 3 group and the water supply plant is in priority 4 group. Rather than including both facilities in group 3, we employ the following approach. Let us suppose that the fire station shows up as a part of a previous priority group's solution, we then force the model to include the water supply plant where the fire station showed up and rerun our model because we know that these two facilities have a dependence. For our example, we could assume that the fire station is part of the solution for priority 1 group. This means that we would include the water supply plant in priority 1 group and rerun our models. In conclusion, because of the interdependency between the fire station and water supply plant, the two facilities may end up changing their priority groups. It is important to highlight that changing the priority group for the two facilities is not always going to be the case.

Dynamic resources. Every time a road is restored, it can be used as a resource to rebuild a new one. As a result, the set of resources (roads) is dynamic. The resources' availability is limited by their geographic location because it is not possible to restore a road if there is no access to it. Our models are executed iteratively for each priority group. Once we finish one priority group, we update the road infrastructure system and use it as an input for the next iteration.

In the methodology part of this document, a detailed explanation of how we address all these technical challenges is provided.

4.3 Objectives and Tasks

There were two broad objectives for this research. The first was to develop a methodology and associated mathematical models that can better determine how the roads should be cleaned up or restored after a disaster considering dynamic resources, priorities, and interdependencies among facilities. The second was to conduct a case of study using simulated disaster scenarios that closely resemble past natural disasters to demonstrate the applicability of our methodology and models.

To achieve the objectives mentioned above, the following tasks were completed.

1. *Methodology:* An iterative two-stage process methodology was developed. The first phase determined the roads that need to be restored. The second stage established the optimal schedule for restoring the roads including the crew assignments. The priority groups and dynamic resources were addressed by considering one priority group in an iteration.

2. *Models:* Each stage of the methodology included an optimization model. Stage 1 used a Steiner Tree Formulation to identify the roads that need to be restored. A scheduling formulation was implemented in the second stage to find the crew's schedule that will oversee the restoration process for each road.

3. *Generating data using Hazus:* Case study data related to the impact of a disaster was generated using Hazus. It is a tool developed by the Federal Emergency Management Agency (FEMA). The location of the shelters and facilities that the emergency management team needs to get access to, and the impact on the road infrastructure network was determined using Hazus.

4. *Numerical experiments:* We replicated the 1994 Northridge earthquake and generated multiple scenarios using Hazus to evaluate the applicability of our models and methodology.

V. METHODOLOGY

For the optimal planning of reconstruction activities, we developed a sequential, two-stage approach that starts with a compromised road infrastructure system. The approach determines which roads should be cleaned up or restored and in what order. In addition, the crews' schedule for completing the reconstruction process is established. The approach considers dynamic resources, priorities, and interdependencies among the facilities.

To address a real situation using mathematical models, it was necessary to establish the main characteristics of the models, prepare the data, develop and solve models, and analyze the results.

5.1 Main characteristics of the models

5.1.1 Models' objective

Maximizing the "comfort" of the people affected by the disaster is the main goal. It is important to highlight that we defined comfort as returning victims' life "back to normal" as soon as it is possible. Hence, our objective was to minimize the total completion time to recover the road infrastructure system required to connect the essential facilities. The mathematical models also provide the crews' schedule to complete the reconstruction activities.

5.1.2 Questions answered

- Which roads should be restored?
- What is the optimal order to restore them?
- What is the assignment of crews to restore the roads?

5.1.3 Information needed

- The availability of the transportation infrastructure after a disaster.
- The locations of hospitals, schools, shelters, and other facilities that the emergency manager considers as relevant.
- Priority level assigned by emergency managers to the facilities to indicate the importance of restoring access to them.
- Interdependencies among facilities identified by emergency managers.
- The locations of the crews that can restore the roads.
- Estimates of the time required to restore each of the roads.

5.1.4 Assumptions

- Each road must be restored 100%. No partial restoration is considered.
- Each road is bidirectional. This condition was also stated by Akbari and Salman (2017).
- The crews are located at specific nodes in the network in a way similar to that of Akbari and Salman (2017).
- The crews are identical in terms of the time that they need to restore a road (Nurre et al., 2012).
- The crews have the equipment and knowledge to work on any type of road.
- The crews transportation time is not considered.
- The road infrastructure system will not be 100% restored.

5.2 Data selection and preparation

Obtaining data is a challenging task for the post-disaster activities. However, the Federal Emergency Management Agency (FEMA) has developed a tool called Hazus. Hazus estimates potential losses for buildings and infrastructure as well as the impacts on populations as a result of disasters such as earthquakes, hurricanes, and floods. Hazus has been successfully used by different researchers. A complete list can be obtained at https://www.fema.gov/hazus-success-stories.

In this dissertation, we replicated the 1994 Northridge earthquake using Hazus. The information that Hazus provides allowed us to know the availability of the road infrastructure system after such disaster. It also provided information about the essential facilities' locations that were included in the models.

5.3 Methodology and Models

Figure 7 shows the 2-stage process that was developed to answer the three research questions listed in Section 5.1.2. This 2-stage process was executed iteratively for each priority group as shown in Figure 8. The first stage identified the roads that should be restored. To do that, we used a Steiner Tree formulation for all the shelters and facilities (nodes) involved in the priority group under consideration. The objective was to determine the list of jobs (roads) that needed to be scheduled for the restoration process. The second stage created the schedule of the jobs and identified the crew that will be responsible for the restoration process for each road. The objective for selecting the best schedule was to minimize the total restoration time.

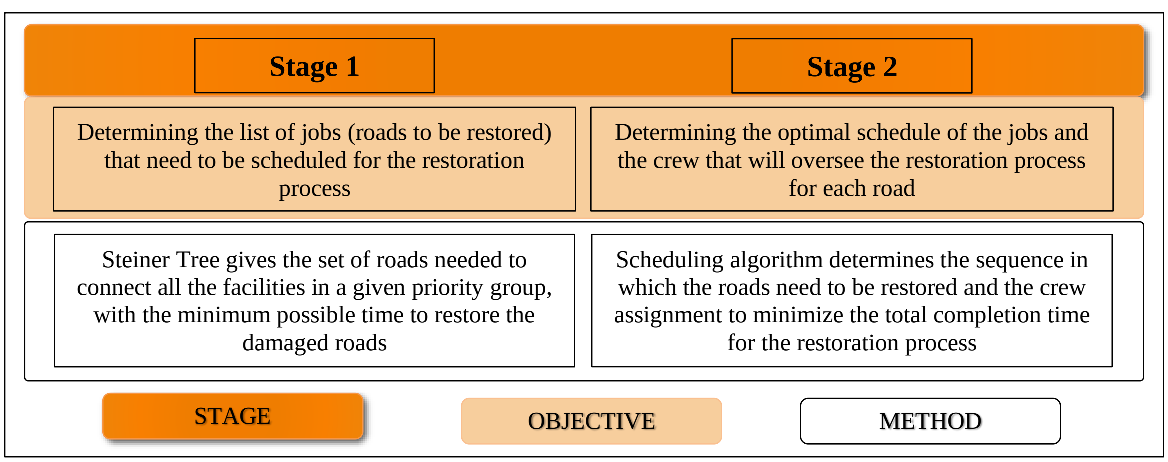


Figure 7. Illustration of the 2 – stage process

The emergency manager decides priorities for facilities to which access needs to be restored. The two -stage process needs to be executed as many times as there are priority groups and one last time for the remaining facilities (Figure 8). The key idea is to update the condition of the road network at the end of each iteration and use it as an initial condition for the next one. The last iteration is for finding out the schedule for the jobs related to the locations that were not assigned to a priority group. It is important to remember that because of interdependencies, it is possible that a lower priority facility might have to be considered in a higher priority group.

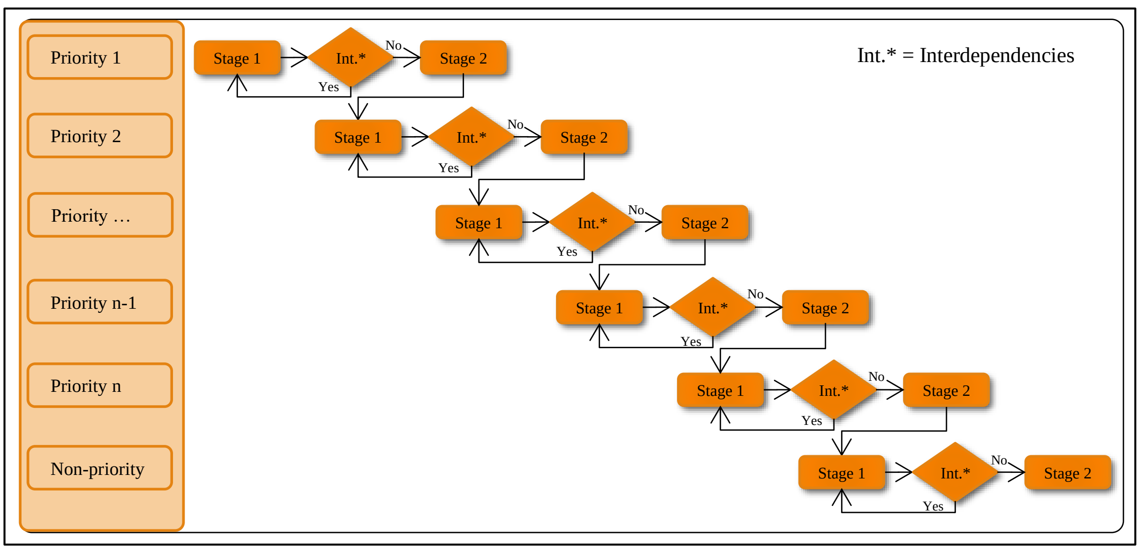


Figure 8. Illustration of the iterative nature of the methodology

It should also be noted that our methodology was influenced by the recommendations/suggestions contained in Nurre et al. (2012) and Akbari and Salman (2017). In particular, the suggested use of shortest paths between sets of critical nodes in Nurre et al. (2012) and the multiperiod idea with network condition updates between periods mentioned in Akbari and Salman (2017)

5.4 An Illustrative Example

In order to explain the methodology, an example of a road infrastructure system impacted by a disaster was created. The system includes 27 facilities, 53 roads that could be restored, and 3 roads in working condition. In addition, 2 shelters, 3 priority groups, 2 crews, and 2 interdependencies were assumed. Figure 9 represents this road infrastructure. It is important to notice, that each road has a number on it which indicates the time required for reconstruction. We assumed two interdependencies one between facilities C and Z and the other between U and G.

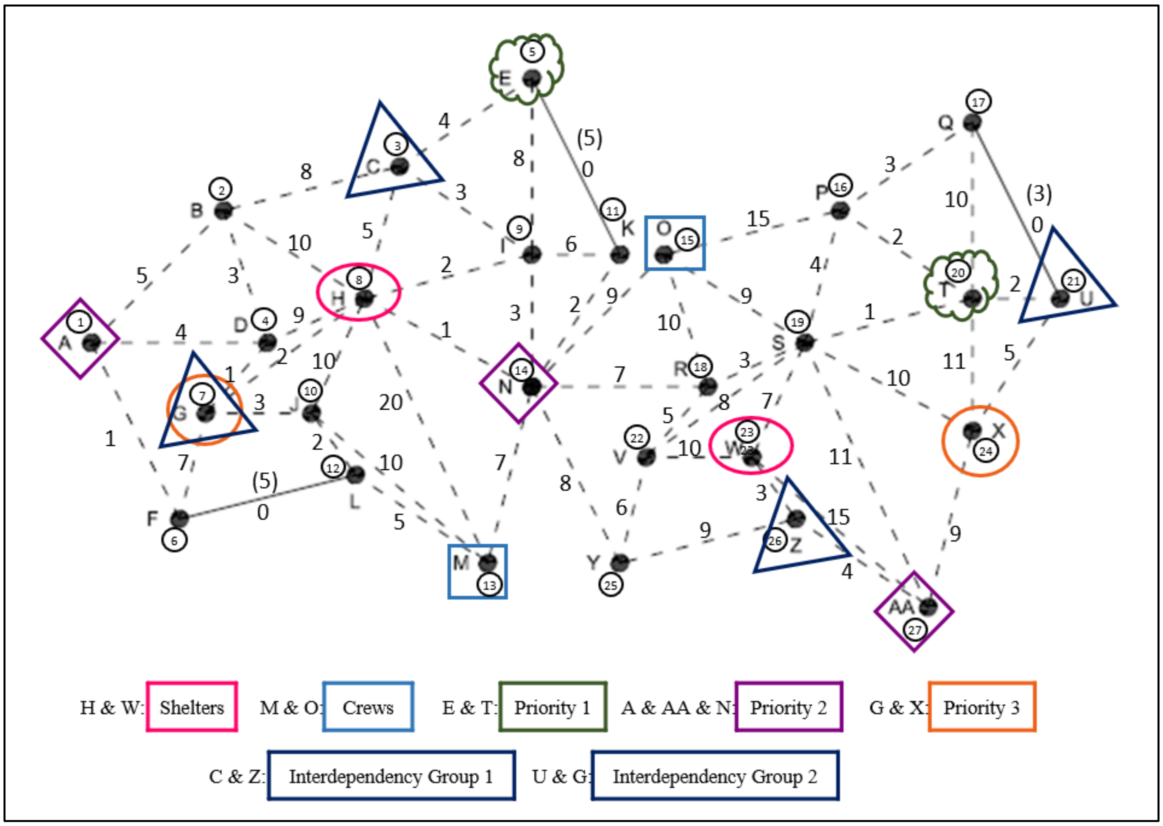


Figure 9. Illustration of a road infrastructure system after a disaster

As it was mentioned before and can be seen in Figure 8, the two-stage process needs to be applied for each priority group. As a result, we will start solving the problem by finding out the list of jobs that need to be done in other to connect shelters H and W with facilities E and T. It is important to notice that shelters H and W with facilities E and T are part of the Priority 1 group. Crews are needed to restore the roads and reestablish these connections. The location of the crews and facilities that need to be connected are shown in Figure 10.

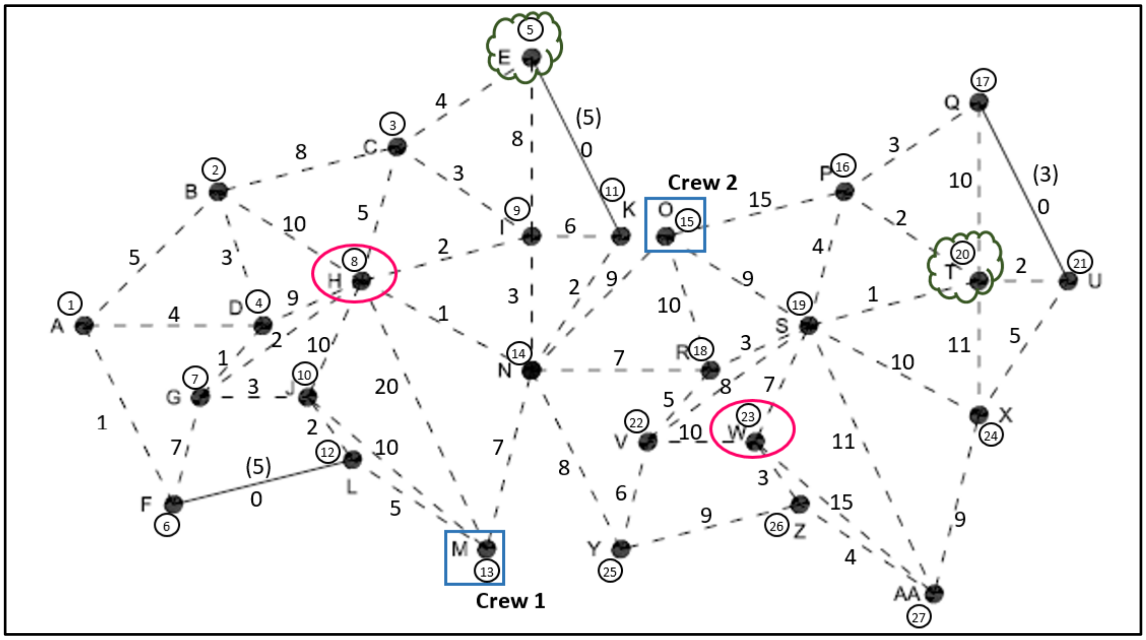


Figure 10. Initial road system for priority 1

After applying the Steiner Tree Formulation, we identified a set of 9 roads that are needed for connections among the Priority 1 facilities as shown in Figure 11. It is important to note that only 8 of them need to be restored as it can be seen in Figure 12. In addition, Figure 12 shows the one-to-one mapping between roads and jobs. This mapping is the starting point for the second stage of the methodology.

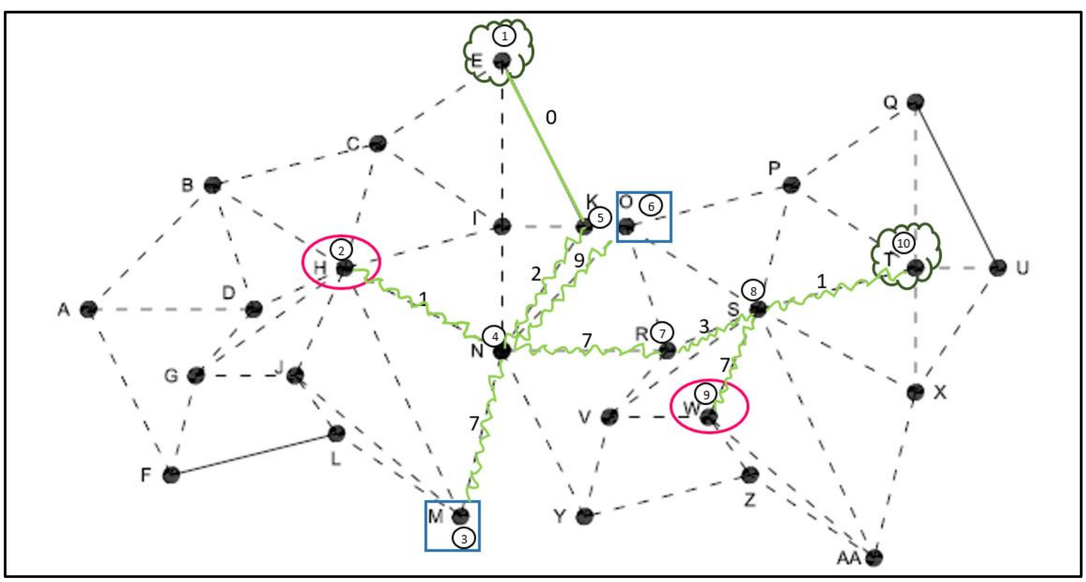


Figure 11. Steiner Tree solution for priority 1 group

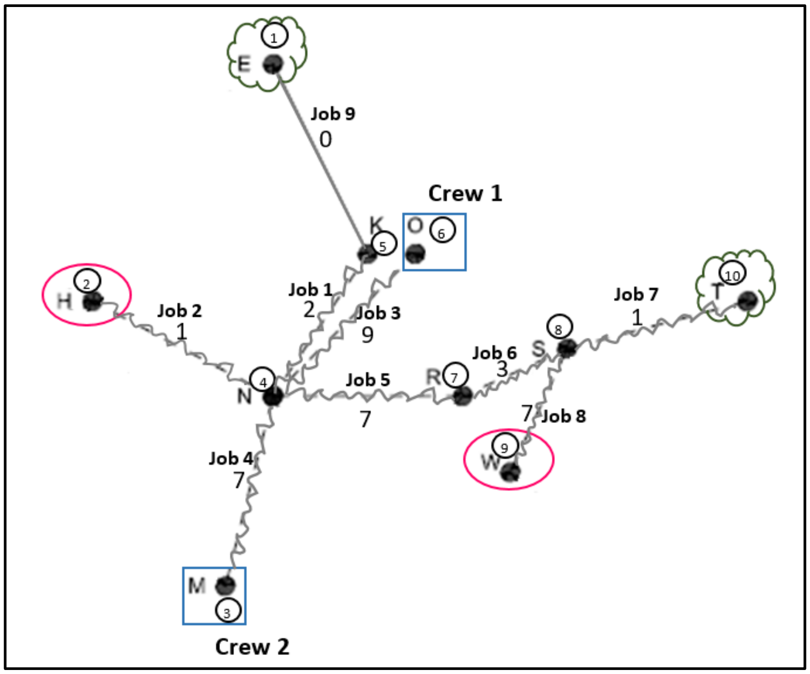


Figure 12. Jobs to schedule for priority 1 group

Stage two of the methodology provided the solution of the scheduling process for each crew which is presented in Figure 13 and Figure 14. Crew one will be in charge of jobs 3, 5, and 6. In other words, crew one will be working on the roads between facilities O-N, N-R, and R-S. The total time that is needed to complete these jobs is 19 time units. Similarly, crew two will need 18 time units to complete jobs 4, 2, 1, 7, and 8. In terms of the roads that need to be restored it means that crew 2 will be incharge of roads between facilities M-N, N-H, N-K, S-T, and S-W.

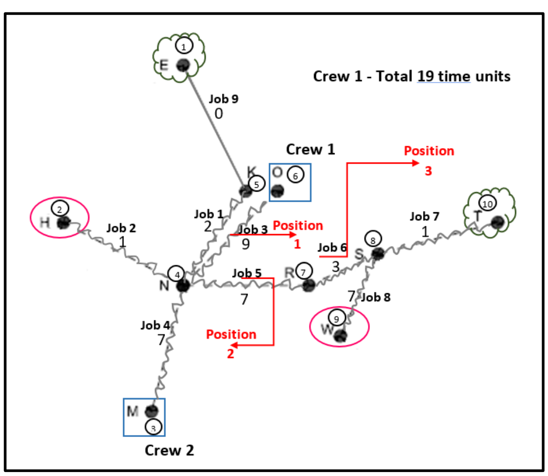


Figure 13. Crew 1 schedule for priority 1

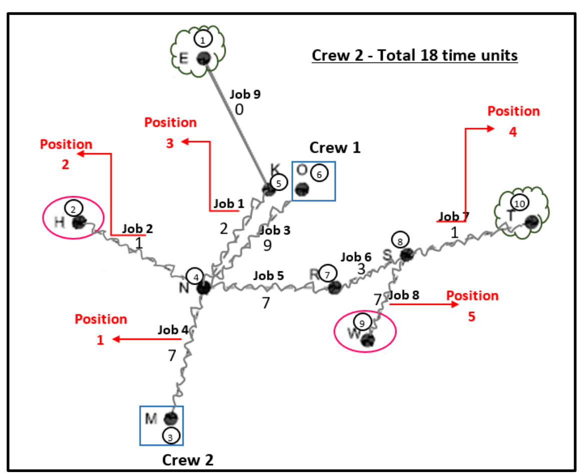


Figure 14. Crew 2 schedule for priority 1

Finally, we updated the road infrastructure system by adding the restored roads to the network and indicating the new initial positions of the crews. This information is considered as the initial road infrastructure system for solving the priority 2 group requirements. A representation of the updated road network is presented in Figure 15.

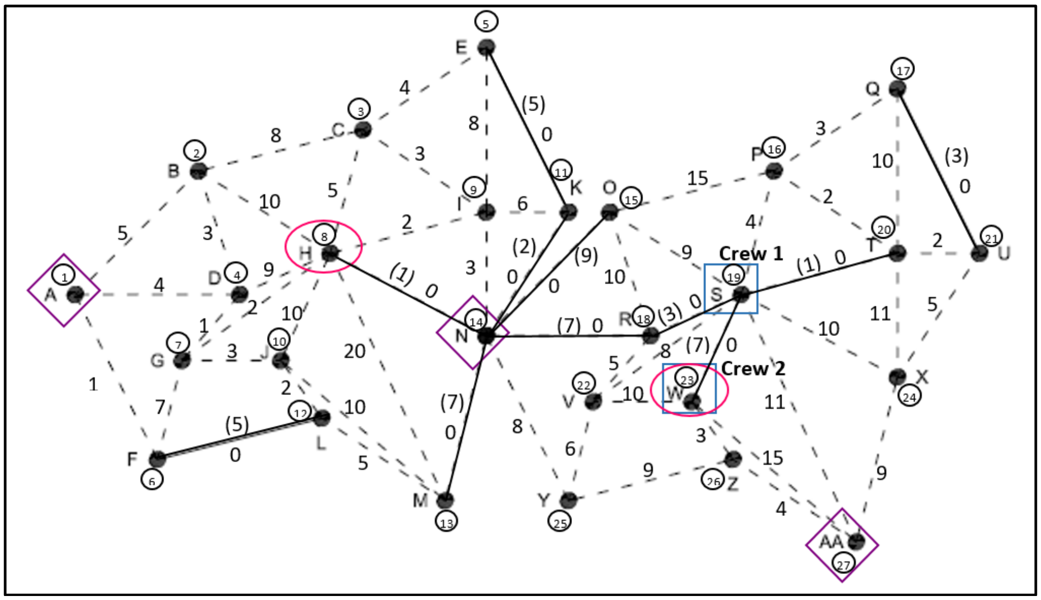


Figure 15. Initial road infrastructure system for priority 2

Stage 1 results after solving the Steiner Tree model are presented in Figure 15. Facility Z is now part of the solution for priority 2. Because of the interdependence between C and Z, C was included as another facility in the priority 2 group. We identified 13 critical roads (Figure 16) and 5 jobs to schedule for the restoration process (Figure 17).

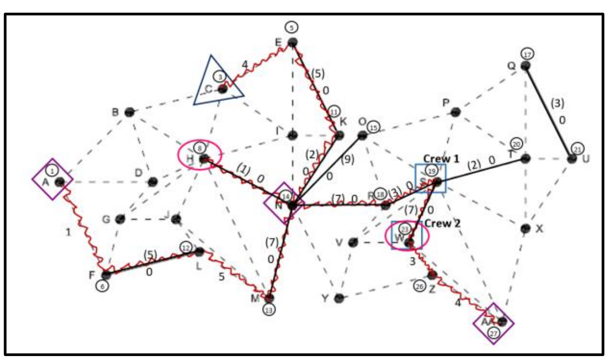


Figure 16. Steiner Tree solution for priority 2

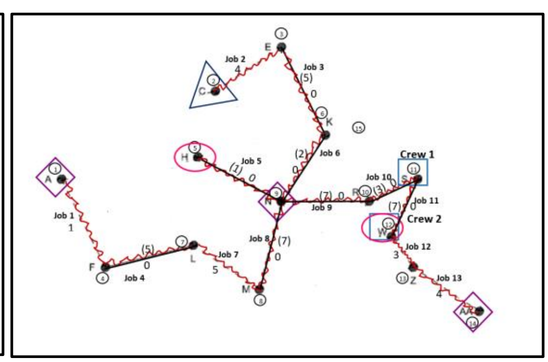


Figure 17. Jobs to schedule for priority 2

Crew one needs to work 9 time units in doing jobs 2, 1, and 13 (Figure 18). In addition, crew 2 will work on jobs 7 and 12 (Figure 19) and will need a total of 8 time units.

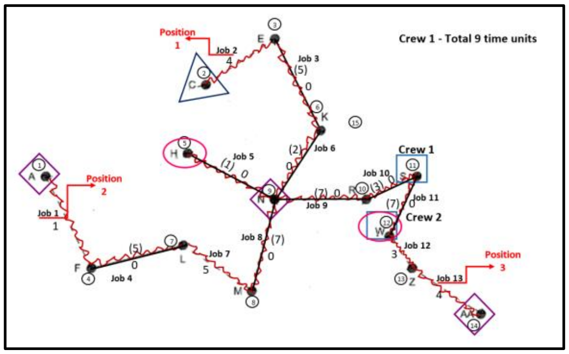


Figure 18. Crew 1 schedule for priority 2

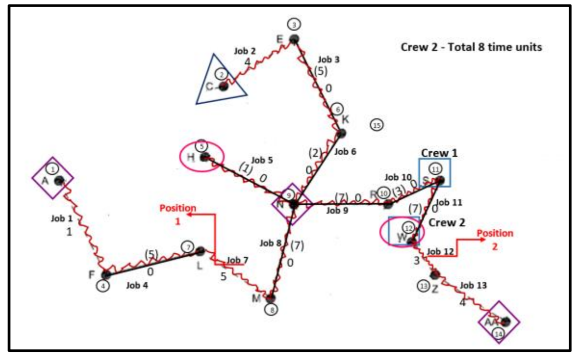


Figure 19. Crew 2 schedule for priority 2

The updated system and initial network for priority 3 is presented in Figure 20. It is important to highlight that G is one of the priority 3 facilities. Knowing that there is an interdependence between G and U, U is included as another priority 3 facility.

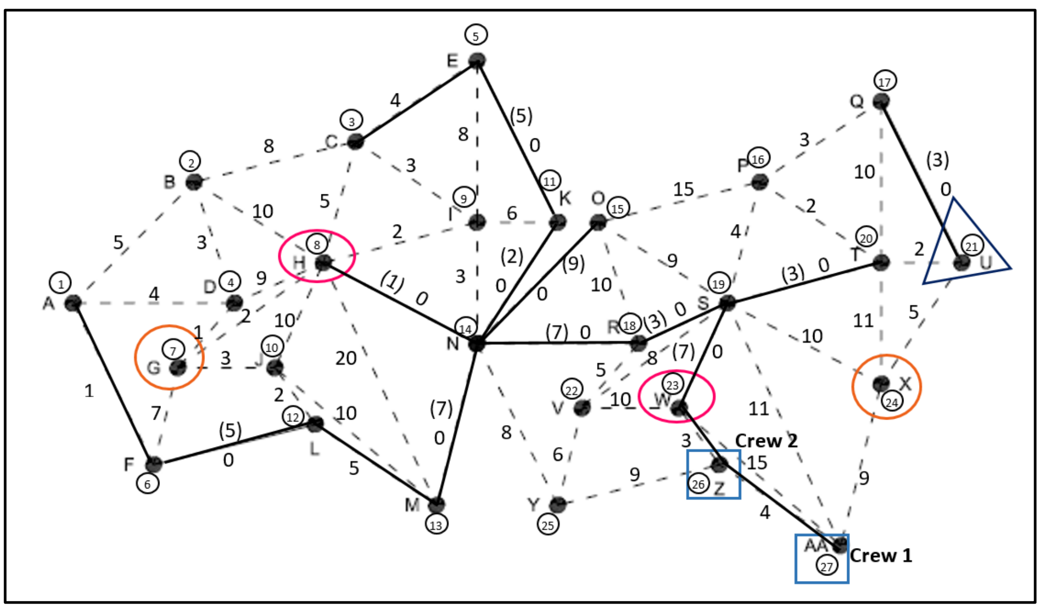


Figure 20. Initial road infrastructure system for priority 3

As before, the two-stage process was applied to the infrastructure system presented in Figure 20. The updated system after this iteration is shown in Figure 21 and is the initial road system for facilities with no priority. It is important to note that some of the non-priority facilities are already connected to the shelters. Hence, they are not included in the analysis.

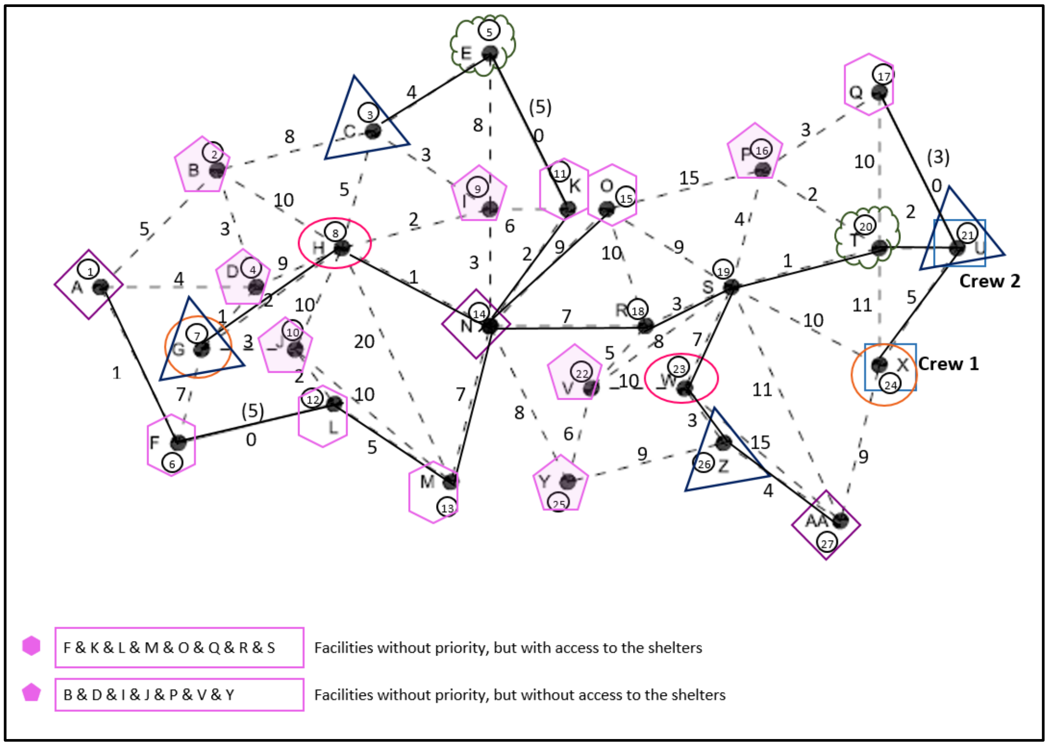


Figure 21. Initial road infrastructure system for facilities with no-priority

After solving the no-priority facilities group, all the facilities are connected. Figure 22 presents the final restored road infrastructure system.

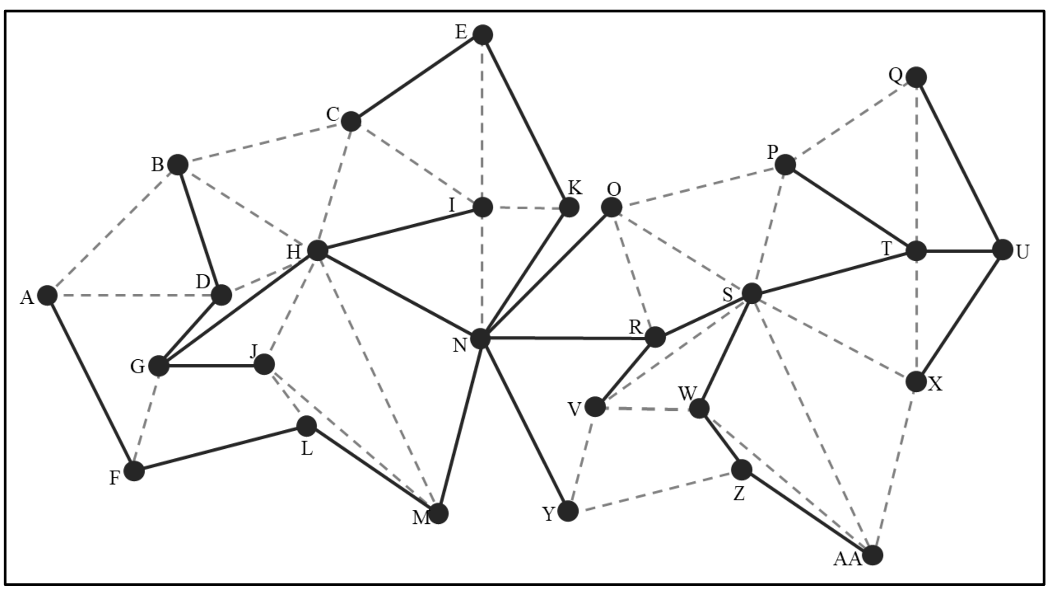


Figure 22. Final restored road infrastructure system

Finally, a summary of the crews' restoration schedule by priority group is presented in Figure 23.

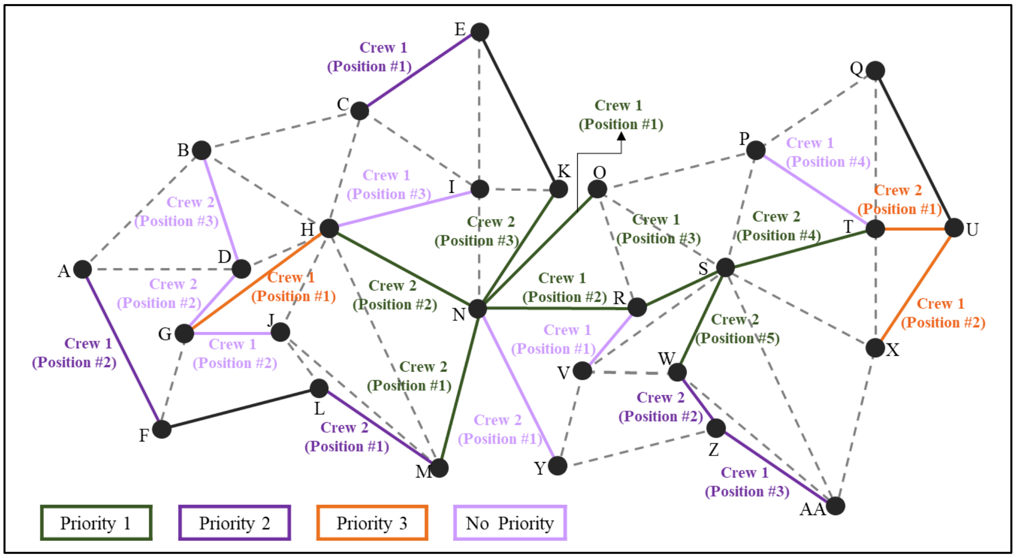


Figure 23. Crews' restoration schedule by priority groups

The optimization models used at each stage of the two-stage approach are presented in the next section.

5.5 Quantitative Models used in the Two-Stage Approach

As it was mentioned before, a Steiner Tree model and a scheduling model were used in the two-stage process. The notation and the algorithm that connects the two models is presented below. This section will be followed by a detailed explanation of each formulation.

<u>Notation</u>

$\mathcal{F}$ is the set of all facilities (shelters, crews, hospitals, etc)

$\mathcal{P}$ is the number of priority groups

p_{f} is the priority group of facility $f \in \mathcal{F}$

$\mathcal{T}$ is the number of interdependency groups

t_f is the interdependency group of facility $f \in \mathcal{F}$

$\mathcal{R}$ is the set of all roads $\{(i,j)\ |arc\ (i,j)$ exists, $i,j \in \mathcal{F}\}$

$\mathcal{D}_{(i,j)}$ is the time for restoring road $(i,j) \in \mathcal{R}$

$\mathcal{D} = \{\mathcal{D}_{(i,j)}|\ (i,j) \in \mathcal{R}\}$

C is the number of crews

I is the set of all initial locations of crews

$I_c \in \mathcal{F}$ is the initial location of crew c

Main Algorithm

$p = 1$

While $p \leq \mathcal{P} + 1$ *It is necessary to run the algorithm until $\mathcal{P}$ +1 because it represents the non-priority group*

Construct $\mathcal{F}^p$, the set of facilities in priority group p

$t = 1$

Solve the Steiner Tree Model: Steiner Tree $(\mathcal{R}, \mathcal{F}, \mathcal{D}, I, \mathcal{F}^p) \Rightarrow \mathcal{R}', \mathcal{F}'$

$(\mathcal{R}, \mathcal{F}, \mathcal{D}, I, \mathcal{F}^p)$ *is the input for the Steiner Tree formulation*

$\mathcal{R}', \mathcal{F}'$ *are outputs of the Steiner Tree formulation.* $\mathcal{R}' \subseteq \mathcal{R}$ *is the set of roads that are part of the Steiner Tree.* $\mathcal{F}' \subseteq \mathcal{F}$ *is the set of all facilities that are part of the Steiner Tree. It is important to note that it is possible that only some of the roads* $\mathcal{R}'$ *need to be repaired.*

Before the scheduling model is applied, it is necessary to check if any of the facilities in $\mathcal{F}'$ *has an interdependency that was not considered in the Steiner Tree solution. If it is the case, we include all the facilities that were not consider in the same interdependency group for the current priority iteration. After that, we rerun the Steiner Tree Model.*

While $t \leq \mathcal{T}$

Construct $\mathcal{F}^t$, the set of facilities in interdependency group t

$\mathcal{F}^t = \{f\ |t_f = t,\ f \in \mathcal{F}\}$

If $f \in \mathcal{F}'$ has not been satisfied, then

For each $f \in \mathcal{F}'$ do $\mathcal{F}^t \cup \mathcal{F}^p \Rightarrow \mathcal{F}^p$/ include all $f \in \mathcal{F}^t$in $\mathcal{F}^p$

Rerun the Steiner Tree Model: Steiner Tree $(\mathcal{R}, \mathcal{F}, \mathcal{D}, I, \mathcal{F}^p) \Rightarrow \mathcal{R}', \ \mathcal{F}'$

$t = 1$

Else

$t = t$+1

End while

Prepare input for the Scheduling Model

The scheduling formulation uses as an input the Steiner Tree solution's information. However, it is necessary to construct three new sets.

Construct the following sets

$\mathcal{R}''$ is the set of roads that need to be reconstructed $\mathcal{R}'' \subseteq \mathcal{R}'$ *In some cases, it is possible that roads in working condition are part of the Steiner Tree solution.*

$\mathcal{D}'$ is the set of restoration times for roads in $\mathcal{R}''$; $\mathcal{D}' = \{ \mathcal{D}_{(i,j,\mathcal{D}(i,j))} | \ (i,j) \in \mathcal{R}''\}$

$\mathcal{N}_{(i,j)}$ is the set of all roads connected to $(i,j) \in \mathcal{R}''$

$\mathcal{N}_{(i,j)} = \{ (i,k) \ | k \neq j \ and \ (i,k) \in \mathcal{R}'\} \cup \{ (j,\ell) \ | \ell \neq i \ and \ (j,\ell) \in \mathcal{R}''\}$

$\mathcal{N} = \{\mathcal{N}_{(i,j)} | \ (i,j) \in \mathcal{R}''\}$

Solve the scheduling formulation

Schedule $(\mathcal{R}'', \mathcal{D}', \ \mathcal{F}', \ \mathcal{C}, \ I, \ \mathcal{N}) \Rightarrow \mathcal{Z}$

$(\mathcal{R}'', \mathcal{D}', \mathcal{F}', \mathcal{C}, \mathrm{I}, \mathcal{N})$ is the input for the scheduling formulation

$\mathcal{Z}$ is the output of the scheduling formulation. It is the assignment of a schedule position and a crew number for each road that needs to be fixed.

Before the models are solved for the next priority group, it is necessary to update the time for restoring the road (i,j) which has been fixed. The new value should be zero. In addition, it is necessary to update the initial location of the crews I_c.

Set $\mathcal{D}_{(i,j)} = 0$ if a road has been scheduled for repair

Update the initial location of the crews I_c

$p = p + 1$

End while

5.5.1 Steiner Tree Model[1]

The problem is to determine the set of roads that connects all the facilities including crew locations for a given priority group, without any cycles and with the minimum possible time to restore the roads. With the objective of explaining this formulation, we use an analogy between the Steiner Tree Model and a Multicommodity Supply Chain Model. We assumed that the crew 1's location (I_1) represents a supplier and the facilities in the current priority group ($k \in \mathcal{F}^p$) represent the demand points. If there is more than one crew, the crews' locations other than crew 1's, $I_2, \ldots, I_{\mathcal{C}}$ are considered as demand points. In both cases, there is just one supplier and it has one unit available for each demand point. The distribution of the units is done by using any of the roads. Note, that roads could have end points that are facility locations themselves. All the facilities that are not in the current priority group are considered as intermediate points and should finish with zero units. In other words, the intermediate points do not have any demand.

<u>Steiner Tree Formulation</u>

As it was mentioned before, we assumed that crew 1's location represents the only supplier available. With multiple crews we treated the additional crew locations as facilities in the priority group for the current iteration. In other words, it is necessary to add $I_2, \ldots, I_{\mathcal{C}}$ to $\mathcal{F}^p$.

Decision variables

$$\mathcal{X}_{(i,j)} = \begin{cases} 1 & if\ road\ (i,j)\ is\ part\ of\ the\ Steiner\ tree \\ 0 & otherwise \end{cases}$$

[1] The base line formulation was presented by Goemans and Myung (1993)

$f_{(i,j)}^{k}$ Flow through road (i,j) going to facility k

$$Minimize \sum_{(i,j)\in\mathcal{R}} \mathcal{D}_{(i,j)}\mathcal{X}_{(i,j)} \quad (1)$$

Subject to:

$$f_{(i,j)}^{k} - f_{(j,i)}^{k} = 1 \qquad i = I_1 \ \ and \ \ k \in \mathcal{F}^p \quad (2)$$

$$f_{(i,j)}^{k} - f_{(j,i)}^{k} = -1 \qquad i = k \ \ and \ \ k \in \mathcal{F}^p \quad (3)$$

$$f_{(i,j)}^{k} - f_{(j,i)}^{k} = 0 \qquad i \neq I_1, \ \ i \neq k \ \ and \ \ k \in \mathcal{F}^p \quad (4)$$

$$f_{(i,j)}^{k} \leq \mathcal{X}_{(i,j)} \quad (5)$$

$$\mathcal{X}_{(i,j)} \leq f_{(i,j)}^{k} \quad (6)$$

$$\mathcal{X}_{(i,j)} + \mathcal{X}_{(j,i)} \leq 1 \quad (7)$$

$$\mathcal{X}_{(i,j)} \in \{0,1\} \qquad \forall\ (i,j) \in \mathcal{R} \quad (8)$$

$$f_{(i,j)}^{k} \geq 0 \qquad \forall\ (i,j) \in \mathcal{R} \ \ and \ \ k \in \mathcal{F}^p \quad (9)$$

Return $\mathcal{R}', \ \mathcal{F}'$

$\mathcal{R}' \subseteq \mathcal{R}$ is the set of roads that are part of the Steiner Tree. $\mathcal{F}' \subseteq \mathcal{F}$ is the set of all facilities that are part of the Steiner Tree.

Objective function (1) minimizes the time for restoring the road infrastructure system that connects the facilities within a priority group. Constraints (2) to (4) ensure flow conservation. Constraint (2) specifies that the facility where Crew 1 is located has one unit available to be sent to each of the facilities that are in the same priority group. Constraint (3) ensures that each facility in the same priority group must finish with one unit. Constraint (4) guarantees that all facilities that are either the crew's location or facilities in the same priority group must finish with zero units. Constraint (5) and (6) require that roads are part of the Steiner tree only if there is flow on them. Constraint (7) indicates that only one direction of a road must be part of the Steiner tree. Then, constraint (8) indicates that there is a binary variable for each road that connects two facilities. Finally, constraint (9) specifies that there is a non-negative variable that represents the flow.

5.5.2 Scheduling Model[2]

The problem is to determine the sequence in which the roads need to be restored and the assignment of the crews to minimize the total completion time for the restoration process. The roads that need to be scheduled is the set $\mathcal{R}''$. $\mathcal{R}''$ could be the same as or a subset of $\mathcal{R}'$ which is the output of the Steiner Tree formulation. The reason for $\mathcal{R}''$ is that the Steiner Tree solution could include roads that are in working condition which do not need to be scheduled.

It is important to mention that if there is just one crew, the objective reduces to identifying the sequence in which the roads need to be restored. Hence, it was necessary to develop two different formulations which are presented below.

$n = |\mathcal{R}''|$ number of roads to be fixed

$M: \mathcal{R}'' \rightarrow \{1, 2, \dots, n\}$

T_r time for completing road r, $r = \mathcal{D}'_{(i,j)}$ where $M_{(i,j)} = r$; $r = 1, 2, \dots, n$

[2] The linear programming formulation was developed using ideas presented by French (1982) and Mokoto (1999)

IR' initial road that needs to be fixed in a single crew formulation

IR'_c initial road that needs to be fixed by crew $c = 1, 2, \dots, \mathcal{C}$

$IR'_c \in \mathcal{N}$. The road with the smallest T_r that is accessible from I_c is selected. $I_{c.} \in \mathcal{F}$ is the initial location of crew $c = 1, 2, \dots, \mathcal{C}$

<u>Single – Crew formulation</u>

Decision variables

$$\mathcal{Z}_{(r,s)} = \begin{cases} 1 & if\ road\ r\ is\ scheduled\ in\ position\ s \\ 0 & otherwise \end{cases}$$

$\mathcal{Y}$ is the maximum completion time for the restoration process

$$Minimize\ \mathcal{Y} \qquad (1)$$

Subject to:

$$\sum_{r} \mathcal{Z}_{(r,s)} = 1 \qquad s = 1, 2, \dots, n \qquad (2)$$

$$\sum_{s} \mathcal{Z}_{(r,s)} = 1 \qquad r = 1, 2, \dots, n \qquad (3)$$

$$\mathcal{Z}_{(r,1)} = 1 \qquad r = IR' \qquad (4)$$

$$\mathcal{Z}_{(r,s)} \leq \sum_{r' \in N_{(r,r')} > 0} \ \sum_{s' \leq s} \mathcal{Z}_{(r',s'-1)} \qquad \forall r \neq IR', \quad s = 1,2, \dots, n \qquad (5)$$

$$\mathcal{Y} - \sum_{r} \sum_{s} \mathcal{Z}_{(r,s)} * T_r \geq 0 \qquad (6)$$

$$\mathcal{Z}_{(r,s)} \in \{0,1\} \qquad \forall r, s \qquad (7)$$

$$\mathcal{Y} \geq 0 \tag{8}$$

Return $\mathcal{Z}$

Objective function (1) minimizes the maximum completion time for the restoration process. Constraint (2) ensures that every road is scheduled just once. Constraint (3) guaranties that each position in the schedule is assigned just once. Constraint (4) indicates the first road that needs to be fixed by the crew. Constraint (5) ensures that a road that needs to be fixed is scheduled only if there is a working road that allows the crew to reach it. Constraint (6) calculates the completion time for the restoration process. Constraint (7) indicates that there is a binary variable for each job assigned in any position of the schedule. Finally, constraint (8) indicates that completion time for the restoration process is represented by a non-negative variable.

<u>Multi – Crew formulation</u>

Decision variables

$$\mathcal{Z}_{(r,s,c)} = \begin{cases} 1 & if\ road\ r\ is\ scheduled\ in\ position\ s\ to\ be\ fixed\ by\ crew\ c \\ 0 & otherwise \end{cases}$$

$\mathcal{Y}$ is the maximum completion time for the restoration process

$$Minimize\ \ \mathcal{Y} \tag{1}$$

Subject to:

$$\sum_{c}\sum_{s}\mathcal{Z}_{(r,s,c)} = 1 \qquad r = 1, 2, \dots, n \tag{2}$$

$$\mathcal{Z}_{(r,1,c)} = 1 \qquad r = IR'_{c}\ \ and\ c = 1, 2, \dots, \mathcal{C} \tag{3}$$

$$\sum_{r}\mathcal{Z}_{(r,s,c)} \leq \sum_{r}\mathcal{Z}_{(r,s-1,c)} \qquad s = 2, 3, \dots, n \quad c = 1, 2, \dots, \mathcal{C} \tag{4}$$

$$\mathcal{Z}_{(r,s,c)} \leq \sum_{r' \in N_{(r,r')}>0} \sum_{s' \leq s} \mathcal{Z}_{(r',s'-1,c)} \qquad \forall r \neq IR', \quad s = 1, 2, \ldots, n \;\; c = 1, 2, \ldots, \mathcal{C} \tag{5}$$

$$\mathcal{Y} - \sum_{r} \sum_{s} \mathcal{Z}_{(r,s,c)} * T_r \geq 0 \qquad c = 1, 2, \ldots, \mathcal{C} \tag{6}$$

$$\mathcal{Z}_{(r,s,c)} \in \{0,1\} \qquad \forall r, s, c \tag{7}$$

$$\mathcal{Y} \geq 0 \tag{8}$$

Return $\mathcal{Z}$

Objective function (1) minimizes the maximum completion time for the restoration process. Constraint (2) ensures that every road is scheduled just one time. Constraint (3) indicates the first road that needs to be fixed by each crew. Constraint (4) guaranties that each position in each crew's schedule is assigned just one time in the proper sequence. Constraint (5) ensures that a road that needs to be fixed is scheduled only if there is a working road that allows the crew to reach it. Constraint (6) calculates the completion time for the restoration process. Constraint (7) indicates that there is a binary variable for each job assigned in any position of crew's schedule. Finally, constraint (8) indicates that completion time for the restoration process is represented by a non-negative variable.

VI. NUMERICAL EXPERIMENTS

Collecting data is a challenging process in the post-disaster activities. However, the Federal Emergency Management Agency (FEMA) has developed a tool called Hazus. Hazus estimates potential losses for buildings and infrastructures as well as the impacts on populations as a result of earthquakes, hurricane winds, and floods (2017). Hazus has been successfully used by different researchers. A complete list can be obtained at https://www.fema.gov/hazus-success-stories.

For the case study, we replicated the 1994 Northridge California earthquake using Hazus.

6.1 Obtaining Data

To be able to apply the methodology presented in Chapter V, it was necessary to use Hazus and Google maps to generate the necessary data. In the following sections, we present detailed information about the type of data that we obtained from these data sources.

6.1.1 Hazus data generation

For obtaining the data required for the models, we followed the process presented below.

a) Creating Northridge Scenario

Knowing that we wanted to replicate the 1994 Northridge earthquake, it was necessary to identify codes for Los Angeles county in California, and the census tract numbers for Northridge. The geographic location of the region of interest is highlighted in dark blue in Figure 24. The codes used to create the Hazus scenario can be seen in Table 3.

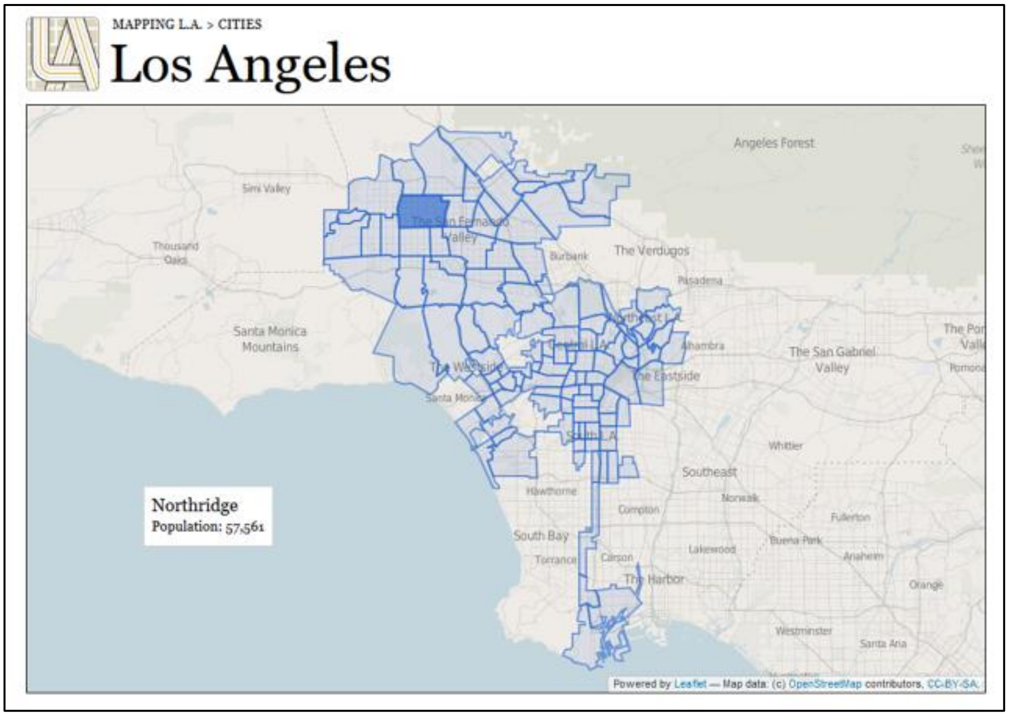


Figure 24. Northridge California geographic location.
Source: http://maps.latimes.com/neighborhoods/city/los-angeles/

Table 3. Northridge´s codes

California State Code	Los Angeles County Code	Northridge Census Tracts - 2010
06	037	111204 111205 111302 113301 113401 115101 115103 115104 115201 115202 115301 115302 115401 115403 115404 117301 117302

Source: United States Census Bureau. http://www.census.gov/geo/reference/geoguide.html

The next step was to create a new study region in Hazus see Figure 25. It was necessary to define a name and to pick the type of disaster. In our case, we picked earthquake.

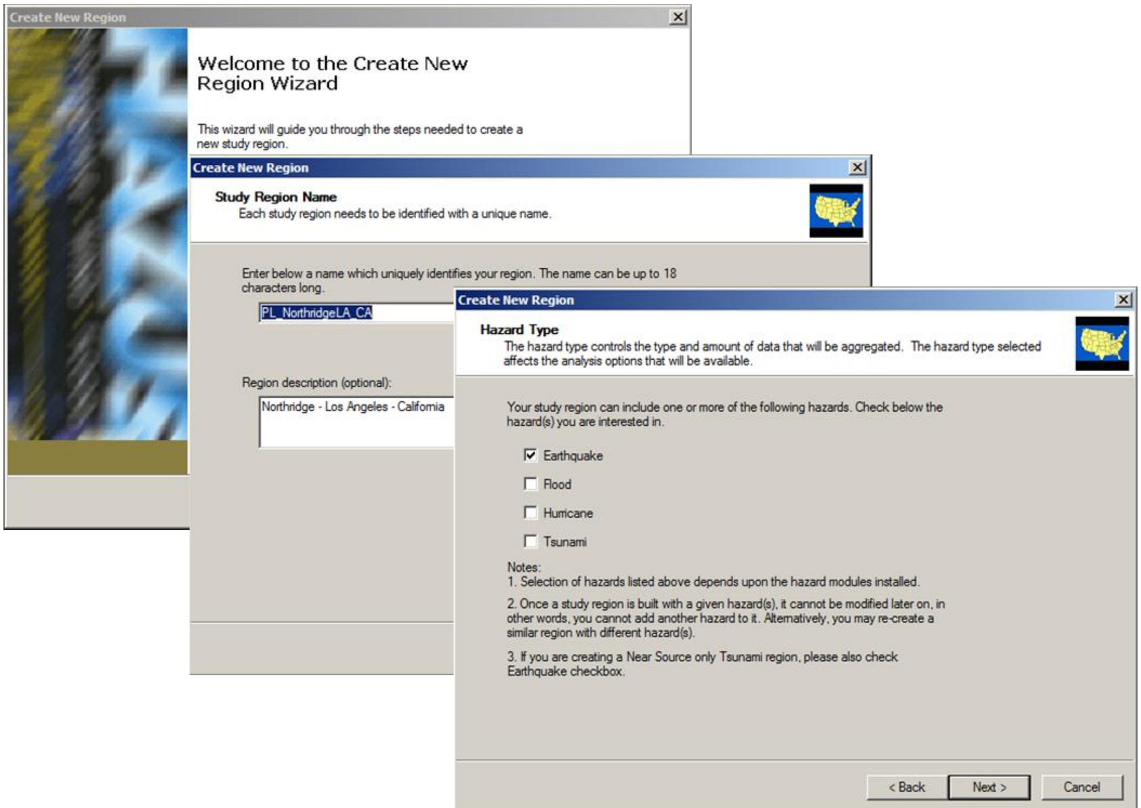


Figure 25. Creating a new study region in Hazus

After creating the new study region, we identified the area that we wanted to use in the simulation. To do that, we entered the information presented in Table 3. Northridge´s codes (See Figure 26 and Figure 27).

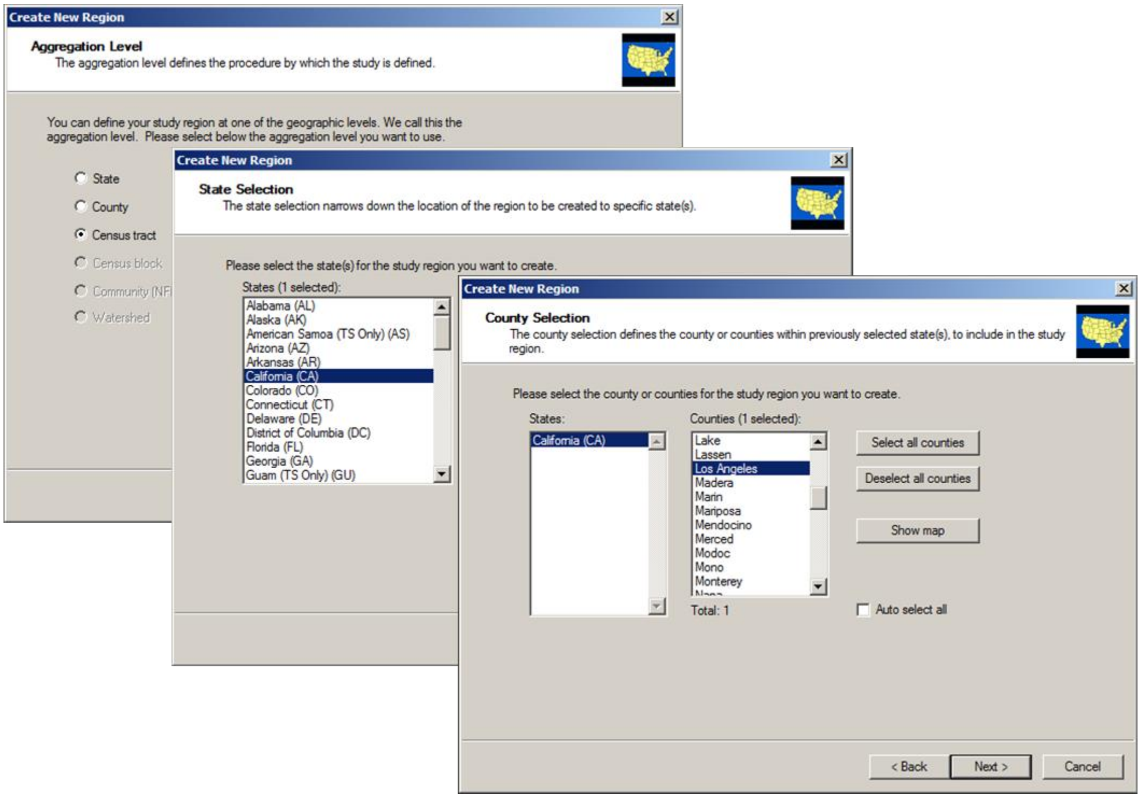


Figure 26. Creating a new region – selecting state and county

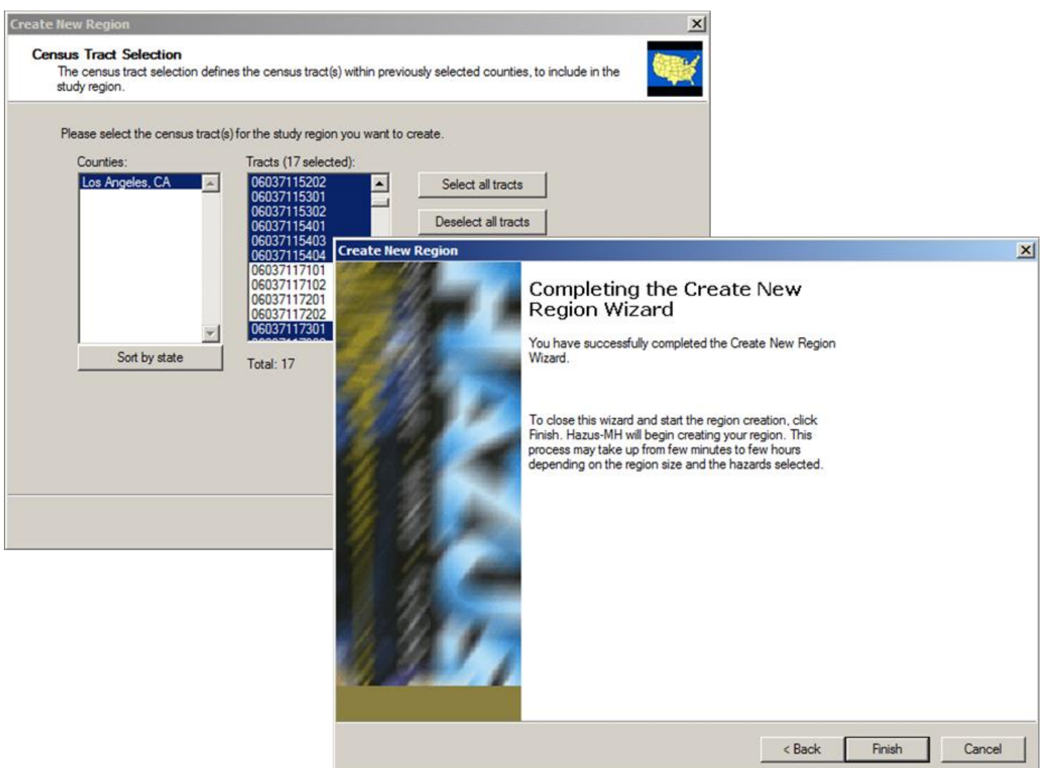


Figure 27. Creating a new region – selecting census tracts

Figure 28 shows that the region creation process was done correctly. To define the characteristics of the event that we want to simulate, we opened the region that was created (see Figure 29 and Figure 30).

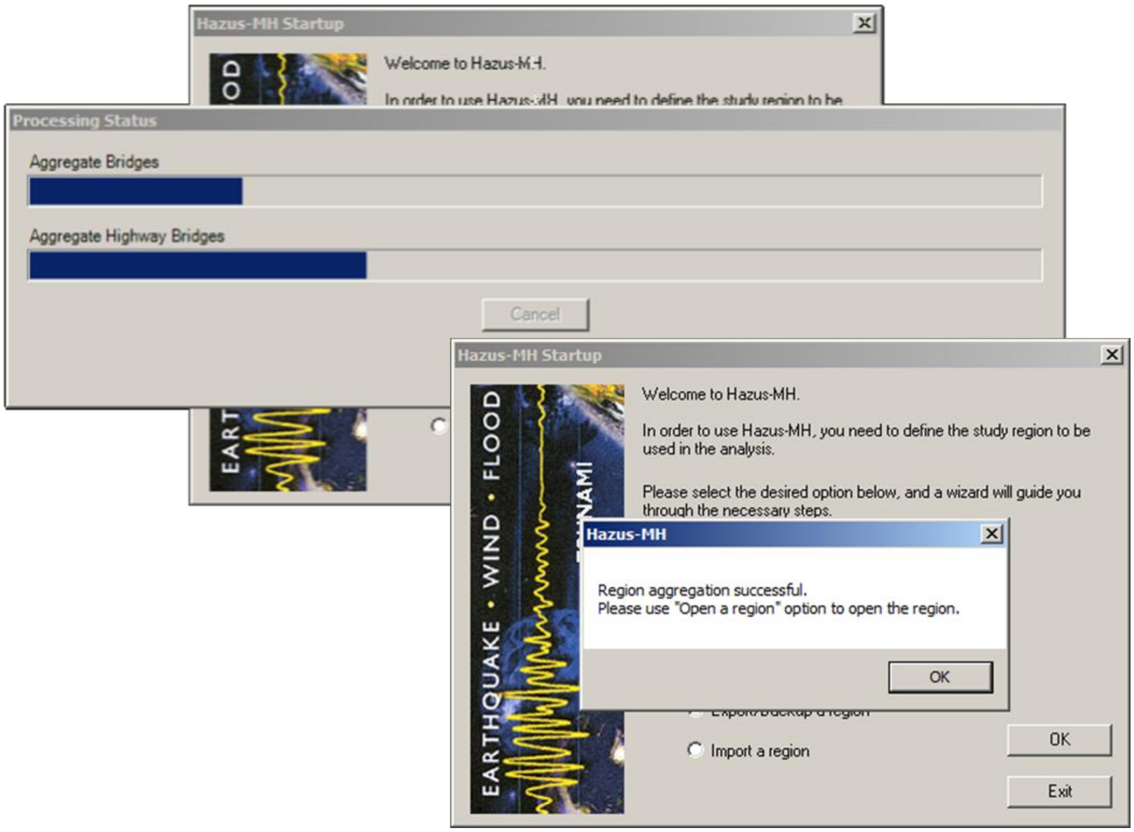


Figure 28. Creating a new region – confirmation

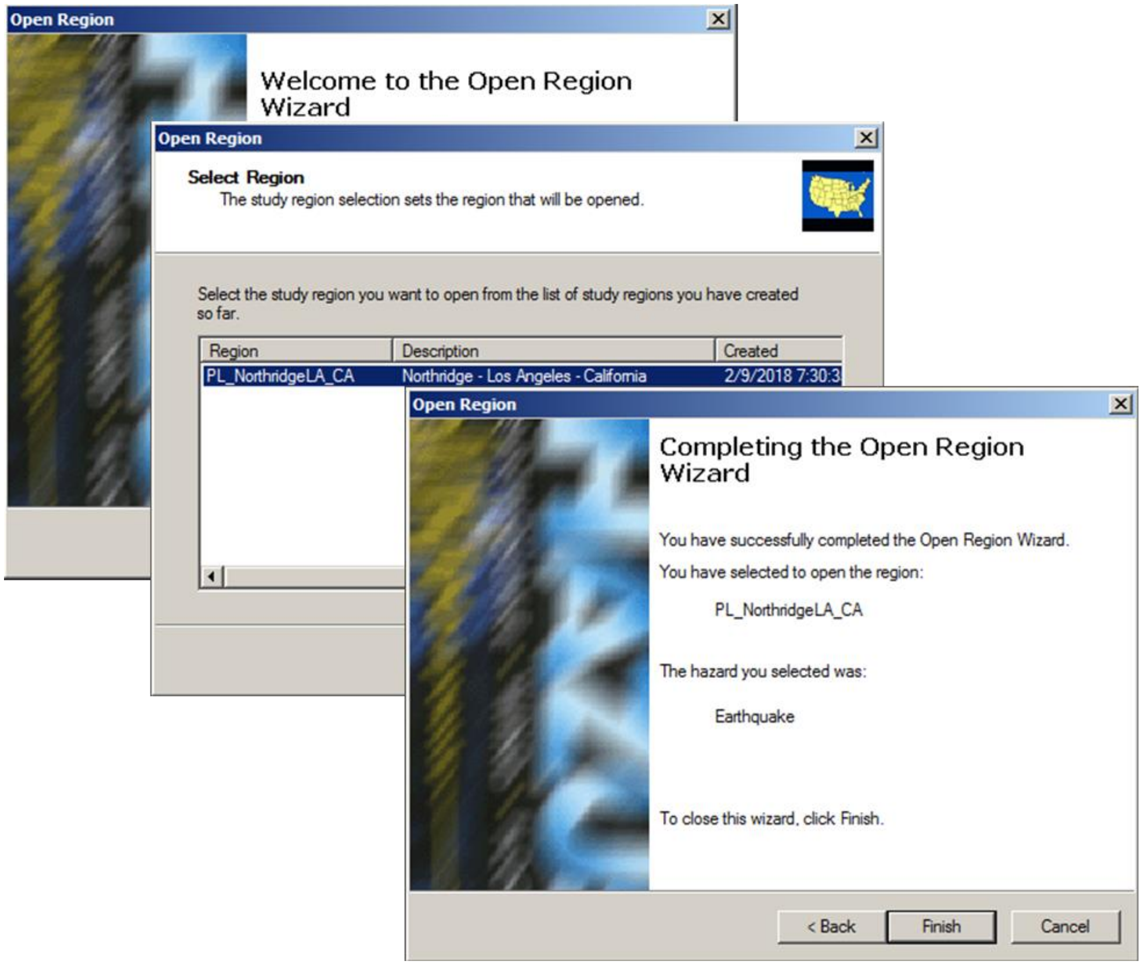


Figure 29. Opening the region of interest

The information related to the Northridge California earthquake available in Hazus is presented in Table 4. The process that was done in order to recreate the Northridge earthquake can be observed in Figure 31 and Figure 32. We decided to use a deterministic hazard as one of the main characteristics of our simulation.

Table 4. Historical epicenter event

	Values
eqEpicenterID	5672
StateID	CA
Magnitude	6.650000
FaultDepth	18
EvetDate	1/17/1994
Latitude	34.21
Longitude	-118.537
Source	USGS

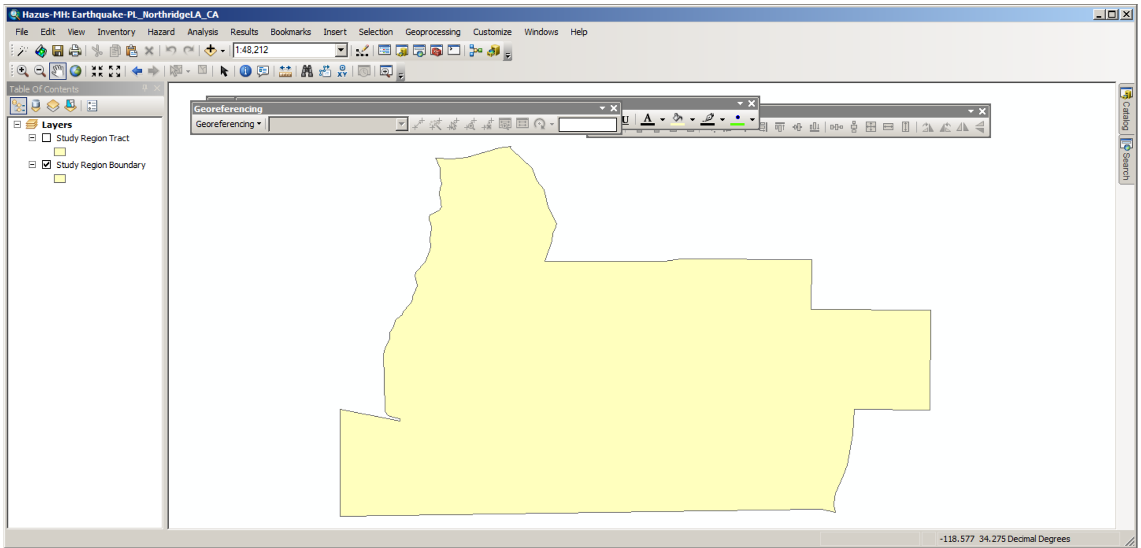


Figure 30. Region, base

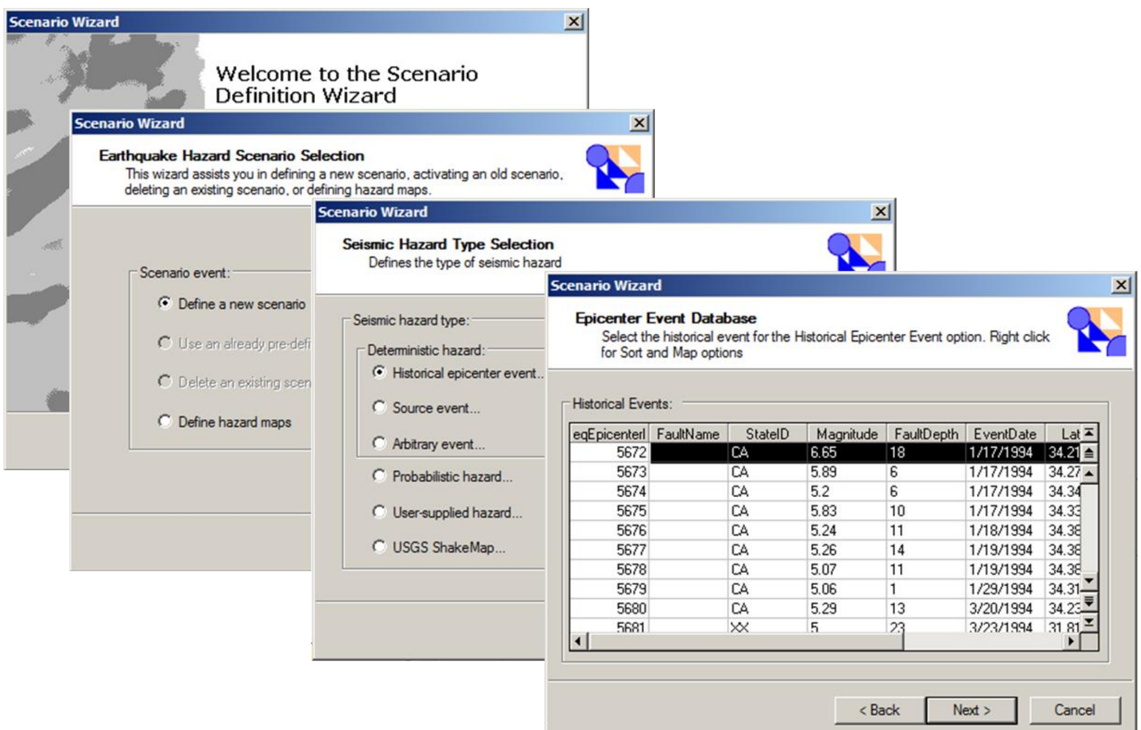


Figure 31. Selecting a historical event – part 1

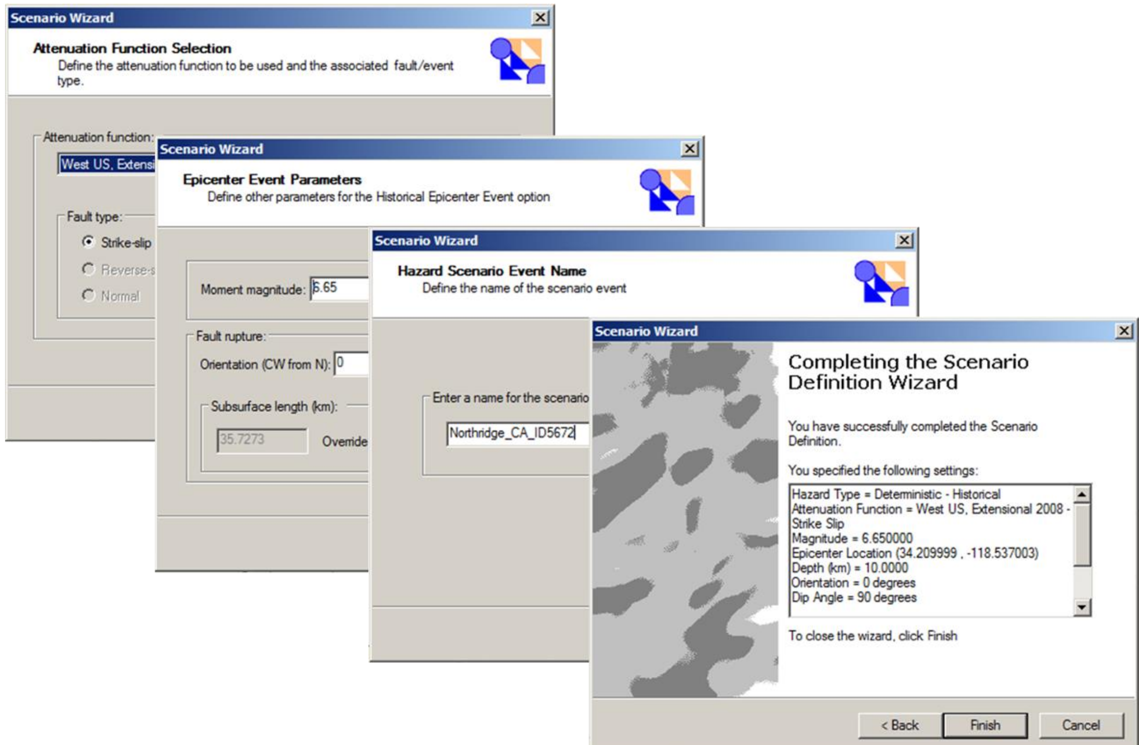


Figure 32. Selecting a historical event – part 2

A summary of the characteristics used in the Hazus simulation of the Northridge earthquake are presented in Table 5.

Table 5. Settings for scenario

Parameters	**Values**
Hazard Type	Deterministic – Historical
Attenuation Function	West US, Extensional 2008 – Strike Slip
Magnitude	6.650000
Epicenter Location	(34.209999 , -118.537003)
Depth (km)	10.0000
Orientation	0 degrees
Dip Angle	90 degrees
Fault Width (km)	10.0
Fault Type	Strike Slip
Subsurface Length (km)	35.727300
Surface Length (km)	23.496300

b) Running analysis for Northridge Scenario

Hazus has an enormous amount of information that can be analyzed under the scenario characteristics that were defined earlier. Two types of data can be extracted from Hazus. The first type is related to the initial information inventory and the second type is related to the simulation results. In other words, the first type will show us the buildings and infrastructures that are located within the Northridge area. While the second type will show us the impact of the disaster in these buildings and infrastructures. It is important to notice, that our methodology does not restore facilities it focuses in restoring the road infrastructure.

To be able to extract the inventory, it is necessary to select one of the options presented in Figure 33. Let us suppose that we want to get the information related to the essential facilities inventory. After we select that option, a new window appears (see Figure 34). The information can be exported as Figure 35 shows.

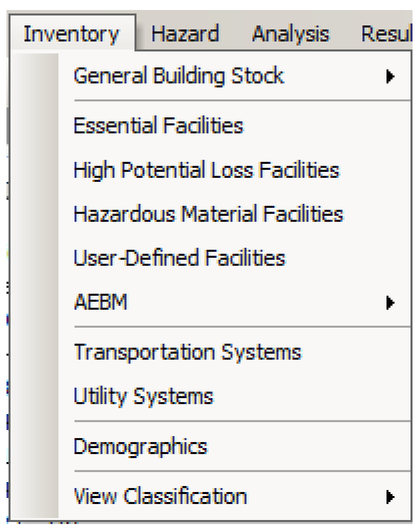


Figure 33. Inventory menu

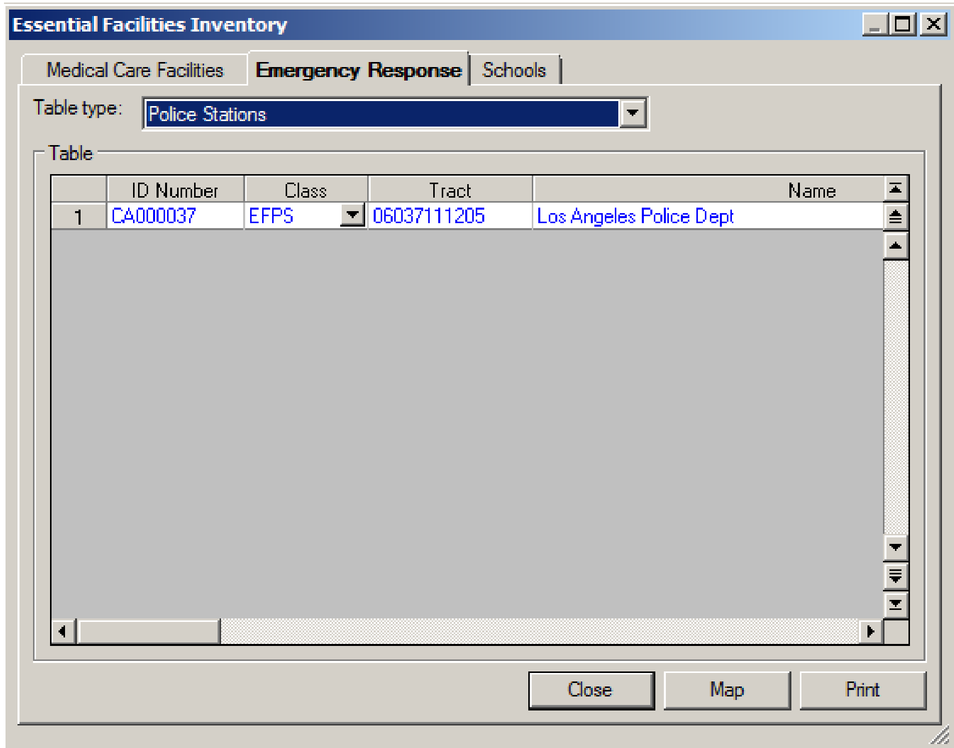


Figure 34. Essential facilities inventory

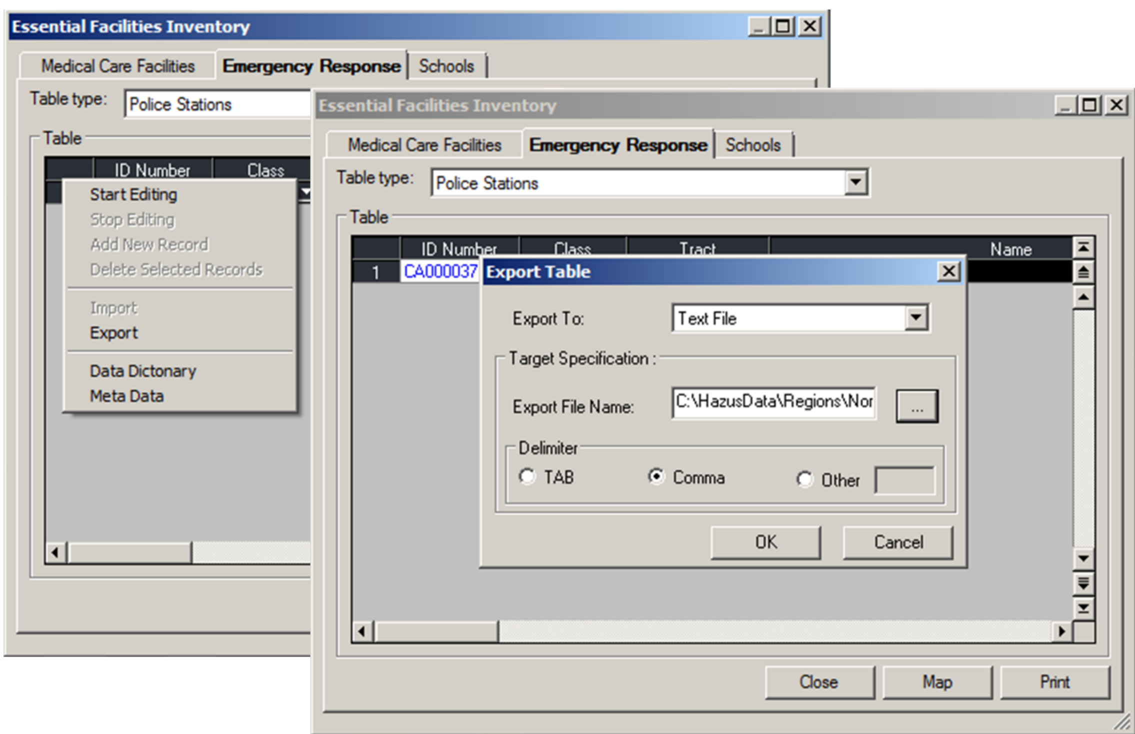


Figure 35. Exporting data inventory (essential facilities)

Figure 36 contains the building and systems inventory list that can be included in the simulation analysis. Once we select the buildings and systems that are going to be affected by the scenario that was created, the simulation starts (See Figure 37).

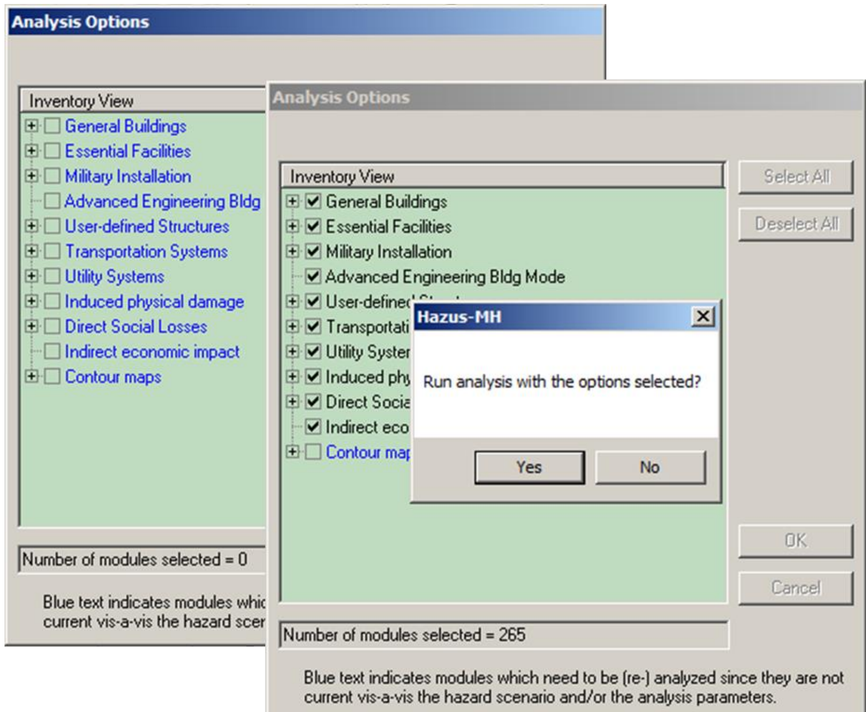


Figure 36. Inventory available for analysis

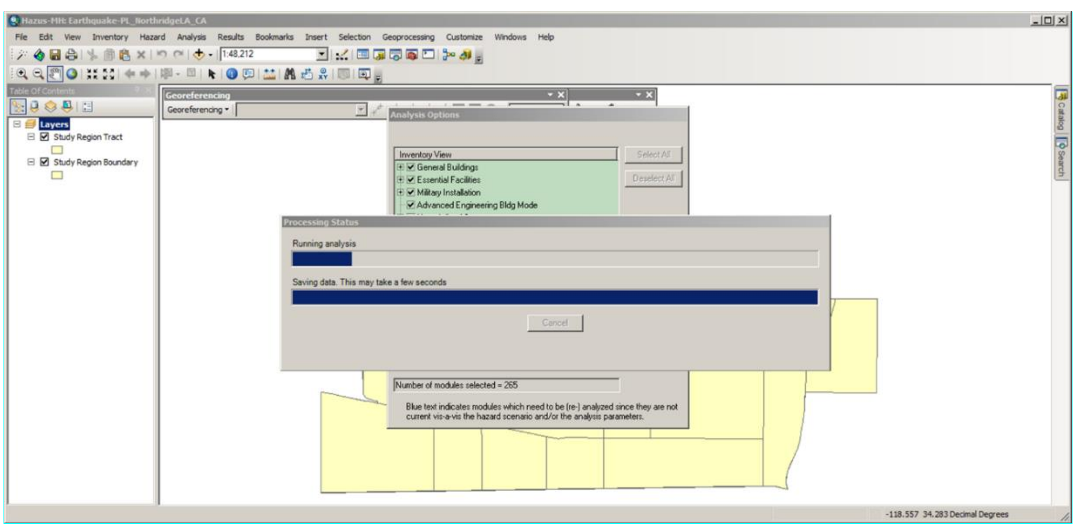


Figure 37. Running analysis

After the simulation was done, it was possible to select the information that is relevant for our analysis. Figure 38 shows the different possibilities that can be used. Figure 39 shows one example of the type of information that can be obtained. In this case, it is the schools that were damaged structurally. The schools are considered as essential facilities as well as emergency response and medical care facilities.

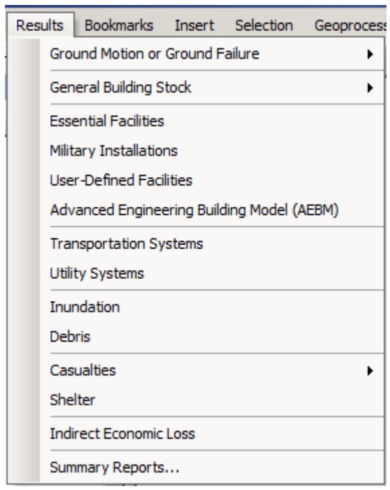
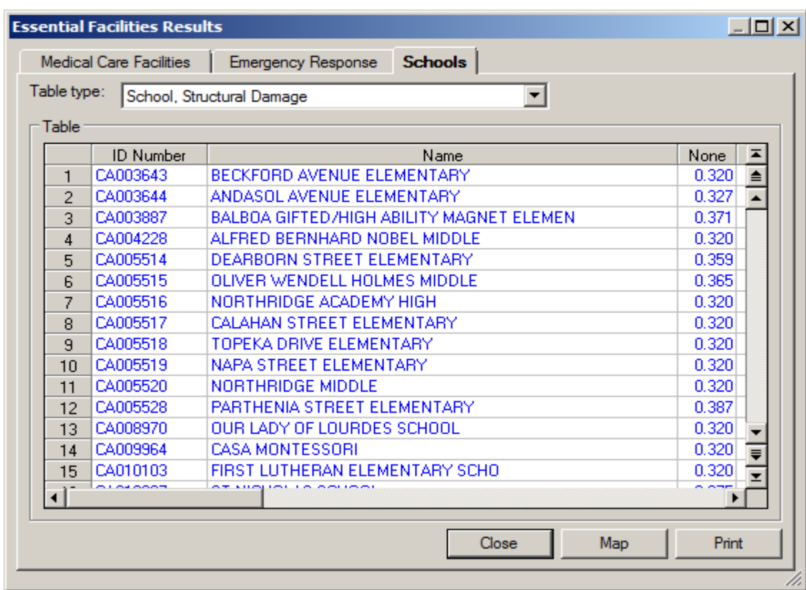


Figure 38. Simulation results



	ID Number	Name	None
1	CA003643	BECKFORD AVENUE ELEMENTARY	0.320
2	CA003644	ANDASOL AVENUE ELEMENTARY	0.327
3	CA003887	BALBOA GIFTED/HIGH ABILITY MAGNET ELEMEN	0.371
4	CA004228	ALFRED BERNHARD NOBEL MIDDLE	0.320
5	CA005514	DEARBORN STREET ELEMENTARY	0.359
6	CA005515	OLIVER WENDELL HOLMES MIDDLE	0.365
7	CA005516	NORTHRIDGE ACADEMY HIGH	0.320
8	CA005517	CALAHAN STREET ELEMENTARY	0.320
9	CA005518	TOPEKA DRIVE ELEMENTARY	0.320
10	CA005519	NAPA STREET ELEMENTARY	0.320
11	CA005520	NORTHRIDGE MIDDLE	0.320
12	CA005528	PARTHENIA STREET ELEMENTARY	0.387
13	CA008970	OUR LADY OF LOURDES SCHOOL	0.320
14	CA009964	CASA MONTESSORI	0.320
15	CA010103	FIRST LUTHERAN ELEMENTARY SCHO	0.320

Figure 39. Essential facilities results- school, structural damage

c) Northridge scenario results

As a result of the simulation that replicated the 1994 Northridge earthquake, we were able to obtain the following information from Hazus.

- List of bridges affected by the disaster
- Geographic location of the essential facilities and bridges
- Statistics related to the reconstruction time of bridges

As a summary of the results, we can highlight that 33 essential facilities that are located in the area impacted by the earthquake. In addition, the list of 19 bridges that would be damaged if there were an earthquake in Northridge, CA, (see Figure 40). Table 6 presents the type, Hazus id, name, and address of the facilities that are located in the area impacted by the earthquake. In addition, Table 7 shows the information related to the bridges affected. It is important to notice that for this scenario no highway segments were damaged. As can be seen in Table 8 all of them are 100% functional. As a complement, Table 9 contains some of the statistics related to functionality of the bridges.

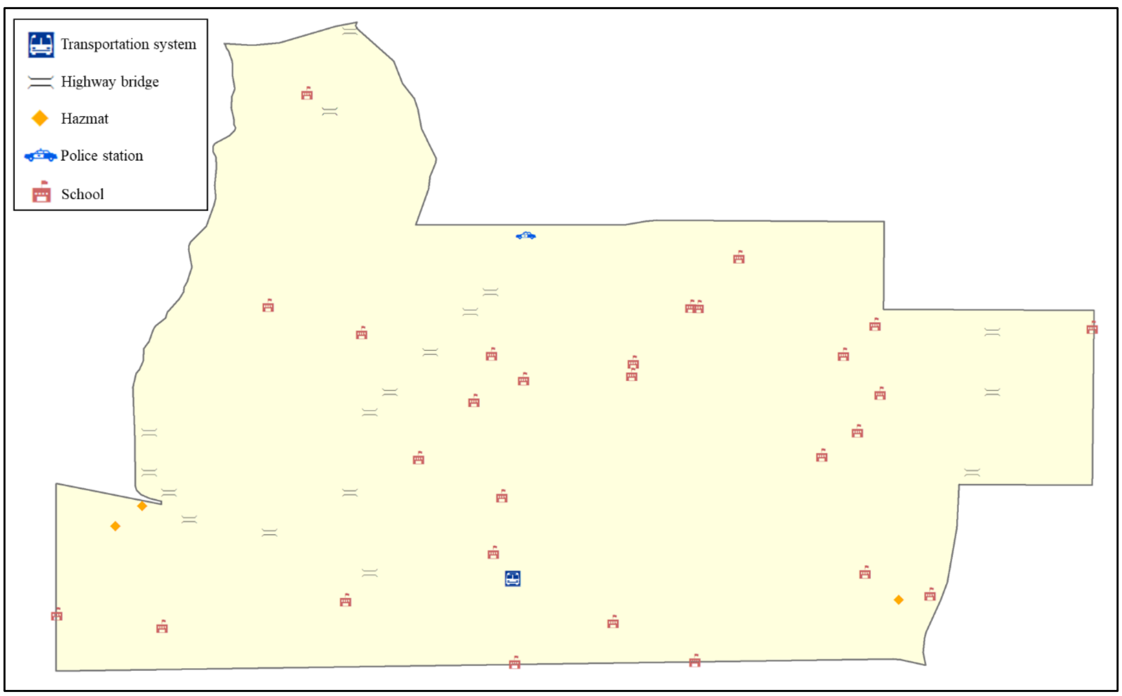


Figure 40. Facilities located in the area and bridges affected by Northridge earthquake

Table 6. Facilities located in the area impacted by Northridge earthquake

No.	Type	Id	Name	Address
1	Police Station	CA000037	Los Angeles Police Dept	10250 Etiwanda Ave
2	School	CA003643	Beckford Avenue Elementary	19130 Tulsa St.
3	School	CA003644	Andasol Avenue Elementary	10126 Encino Ave.
4	School	CA003887	Balboa Gifted/High Ability Magnet Elemen	17020 Labrador St.
5	School	CA004228	Alfred Bernhard Nobel Middle	9950 Tampa Ave.
6	School	CA005514	Dearborn Street Elementary	9240 Wish Ave.
7	School	CA005515	Oliver Wendell Holmes Middle	9351 Paso Robles Ave.
8	School	CA005516	Northridge Academy High	9601 Zelzah Ave.
9	School	CA005517	Calahan Street Elementary	18722 Knapp St.
10	School	CA005518	Topeka Drive Elementary	9815 Topeka Dr.
11	School	CA005519	Napa Street Elementary	19010 Napa St.
12	School	CA005520	Northridge Middle	17960 Chase St.
13	School	CA005528	Parthenia Street Elementary	16825 Napa St.
14	School	CA008970	Our Lady Of Lourdes School	18437 Superior St
15	School	CA009964	Casa Montessori	17633 Lassen Street
16	School	CA010103	First Lutheran Elementary Scho	18355 Roscoe Boulevard
17	School	CA010337	St Nicholas School	9501 Balboa Blvd
18	School	CA010338	Highland Hall Waldorf School	17100 Superior Street
19	School	CA010339	Northpoint School	9650 Zelzah Ave
20	School	CA010640	Los Angeles Baptist Hs	9825 Woodley Ave
21	School	CA011783	Countryside Preparatory School	8756 Canby Avenue
22	School	CA012317	San Fernando Valley Academy	17601 Lassen St
23	School	CA012393	Kidsville Usa	8464 Corbin Ave
24	School	CA012395	Abc Educational Center	18510 Plummer St
25	School	CA012500	Child & Family Studies Center	18330 Halsted St
26	School	CA012653	Our Redeemer Lutheran School	8520 Winnetka Avenue
27	School	CA012654	Knollwood Pre School & Kgn	17034 Parthenia St
28	School	CA012655	Pinecrest School-Whiteoak	17643 Roscoe Blvd
29	School	CA013049	New World Moutessori School	Po Box 8463
30	Hazardous Materials	CA001715	Micro Matic Usa Inc.	19791 Bahama St.
31	Hazardous Materials	CA001718	3m Pharmaceuticals	19901 Nordhoff St.
32	Hazardous Materials	CA001723	Harman Motive Inc.	8500 Balboa Blvd.
33	BUS	CA000019	R & D Transportation Svc	18333 Eddy St # 3

Table 7. Bridges affected by Northridge earthquake

No.	Id	Name	Latitude	Longitude
1	CA022003	SR 118	34.266670	-118.548330
2	CA022004	TAMPA AVE-W118 ON	34.266670	-118.548330
3	CA022005	E118-TAMPA AVE OFF	34.266670	-118.548330
4	CA022124	TAMPA AVE	34.273330	-118.546670
5	CA023228	CORBIN AVE	34.235000	-118.561670
6	CA023285	LASSEN ST	34.250000	-118.536670
7	CA023303	NORDOFF ST	34.235000	-118.546670
8	CA023305	NORDHOFF ST	34.236670	-118.495000
9	CA023319	PARTHENIA ST	34.228330	-118.545000
10	CA023323	HAYVENHURST ST	34.243330	-118.493330
11	CA023324	PLUMMER ST	34.241670	-118.545000
12	CA023327	RESEDA BLVD	34.251670	-118.535000
13	CA023355	TAMPA AVE	34.231670	-118.553330
14	CA023389	WILBUR AVE	34.243330	-118.543330
15	CA023398	YOLANDA AVE	34.246670	-118.540000
16	CA023686	NORDHOFF PLACE	34.236670	-118.563330
17	CA023687	PRAIRIE ST	34.240000	-118.563330
18	CA023688	HAYVENHURST AVE	34.248330	-118.493330
19	CA023846	NORDHOFF WAY	34.232780	-118.560000

Table 8. Highway segments affected by Northridge earthquake

No.	Id	Name	Length	Comment	Functionality at Day 1 (%)
1	CA003813	BALBOA BLVD	2.288830	Urban Principal Arterial	100.00
2	CA006146	BALBOA BLVD	1.636340	Urban Principal Arterial	100.00
3	CA006669	BALBOA BLVD	2.415380	Urban Principal Arterial	100.00
4	CA007076	BALBOA BLVD	1.626140	Urban Principal Arterial	100.00
5	CA010730	BALBOA BLVD	3.624740	Urban Principal Arterial	100.00
6	CA010731	BALBOA BLVD	0.141650	Urban Principal Arterial	100.00
7	CA010732	BALBOA BLVD	2.309440	Urban Principal Arterial	100.00
8	CA006942	DEVONSHIRE ST	0.025682	Urban Principal Arterial	100.00
9	CA006943	DEVONSHIRE ST	1.595520	Urban Principal Arterial	100.00
10	CA008284	DEVONSHIRE ST	6.258850	Urban Principal Arterial	100.00
11	CA008285	DEVONSHIRE ST	1.202100	Urban Principal Arterial	100.00
12	CA008286	DEVONSHIRE ST	3.187600	Urban Principal Arterial	100.00
13	CA010243	DEVONSHIRE ST	0.209946	Urban Principal Arterial	100.00

No.	Id	Name	Length	Comment	Functionality at Day 1 (%)
14	CA010245	DEVONSHIRE ST	0.895283	Urban Principal Arterial	100.00
15	CA010246	DEVONSHIRE ST	0.231678	Urban Principal Arterial	100.00
16	CA010248	DEVONSHIRE ST	0.259821	Urban Principal Arterial	100.00
17	CA009000	I405	0.220695	Urban Interstate	100.00
18	CA009002	I405	0.232548	Urban Interstate	100.00
19	CA009004	I405	0.415882	Urban Interstate	100.00
20	CA009007	I405	0.952403	Urban Interstate	100.00
21	CA010240	I405	0.404130	Urban Interstate	100.00
22	CA010242	I405	0.411346	Urban Interstate	100.00
23	CA010244	I405	1.711550	Urban Interstate	100.00
24	CA010247	I405	0.324069	Urban Interstate	100.00
25	CA014246	I405	1.355010	Urban Interstate	100.00
26	CA014249	I405	0.460263	Urban Interstate	100.00
27	CA014251	I405	0.441154	Urban Interstate	100.00
28	CA014253	I405	0.741508	Urban Interstate	100.00
29	CA014339	I405	0.308796	Urban Interstate	100.00
30	CA006671	NORDHOFF ST	1.612530	Urban Principal Arterial	100.00
31	CA006672	NORDHOFF ST	5.074110	Urban Principal Arterial	100.00
32	CA006674	NORDHOFF ST	1.586280	Urban Principal Arterial	100.00
33	CA008302	NORDHOFF ST	3.398810	Urban Principal Arterial	100.00
34	CA010238	NORDHOFF ST	0.794055	Urban Principal Arterial	100.00
35	CA010239	NORDHOFF ST	0.303585	Urban Principal Arterial	100.00
36	CA010241	NORDHOFF ST	0.296546	Urban Principal Arterial	100.00
37	CA013464	NORDHOFF ST	0.395477	Urban Principal Arterial	100.00
38	CA014252	NORDHOFF ST	0.196655	Urban Principal Arterial	100.00
39	CA014924	NORDHOFF ST	0.436643	Urban Principal Arterial	100.00
40	CA014925	NORDHOFF ST	0.987186	Urban Principal Arterial	100.00
41	CA006135	PARTHENIA PL	0.473333	Urban Principal Arterial	100.00
42	CA006136	PARTHENIA ST	0.385809	Urban Principal Arterial	100.00
43	CA006138	PARTHENIA ST	1.211130	Urban Principal Arterial	100.00
44	CA010405	RINALDI ST	1.115140	Urban Principal Arterial	100.00
45	CA010729	RINALDI ST	1.603690	Urban Principal Arterial	100.00
46	CA006147	ROSCOE BLVD	6.250570	Urban Principal Arterial	100.00
47	CA006149	ROSCOE BLVD	1.792750	Urban Principal Arterial	100.00
48	CA007414	ROSCOE BLVD	3.181990	Urban Principal Arterial	100.00
49	CA014245	ROSCOE BLVD	0.221157	Urban Principal Arterial	100.00
50	CA014247	ROSCOE BLVD	0.650112	Urban Principal Arterial	100.00
51	CA014248	ROSCOE BLVD	0.279251	Urban Principal Arterial	100.00
52	CA014250	ROSCOE BLVD	0.306466	Urban Principal Arterial	100.00
53	CA015832	ROSCOE BLVD	0.135984	Urban Principal Arterial	100.00
54	CA015833	ROSCOE BLVD	1.597530	Urban Principal Arterial	100.00

No.	Id	Name	Length	Comment	Functionality at Day 1 (%)
55	CA010611	S BRAND BLVD	1.608410	Urban Principal Arterial	100.00
56	CA007246	S118	3.262090	Urban Freeway or Expressway	100.00
57	CA008999	S118	0.111276	Urban Freeway or Expressway	100.00
58	CA009001	S118	0.379086	Urban Freeway or Expressway	100.00
59	CA009003	S118	0.330655	Urban Freeway or Expressway	100.00
60	CA009128	S118	6.312420	Urban Freeway or Expressway	100.00
61	CA013066	S118	1.853780	Urban Freeway or Expressway	100.00
62	CA014713	S118	0.824341	Urban Freeway or Expressway	100.00
63	CA016208	S118	2.035850	Urban Freeway or Expressway	100.00
64	CA003808	SEPULVEDA BLVD	2.286040	Urban Principal Arterial	100.00
65	CA006134	SEPULVEDA BLVD	0.269311	Urban Principal Arterial	100.00
66	CA006144	SEPULVEDA BLVD	0.763083	Urban Principal Arterial	100.00
67	CA006936	SEPULVEDA BLVD	0.068118	Urban Principal Arterial	100.00
68	CA008303	SEPULVEDA BLVD	0.545346	Urban Principal Arterial	100.00
69	CA009006	SEPULVEDA BLVD	0.838453	Urban Principal Arterial	100.00
70	CA010728	SEPULVEDA BLVD	2.442710	Urban Principal Arterial	100.00
71	CA015268	SEPULVEDA BLVD	0.381901	Urban Principal Arterial	100.00
72	CA015955	SEPULVEDA BLVD	0.951937	Urban Principal Arterial	100.00
73	CA016211	SEPULVEDA BLVD	0.322092	Urban Principal Arterial	100.00
74	CA015834	SEPULVEDA PL	0.385035	Urban Principal Arterial	100.00
75	CA016433	SESNON BLVD	3.730330	Urban Principal Arterial	100.00
76	CA006851	SHERMAN WAY	6.385200	Urban Principal Arterial	100.00
77	CA006852	SHERMAN WAY	1.604260	Urban Principal Arterial	100.00
78	CA006853	SHERMAN WAY	3.196790	Urban Principal Arterial	100.00
79	CA014040	SHERMAN WAY	0.326405	Urban Principal Arterial	100.00
80	CA014319	SHERMAN WAY	0.604480	Urban Principal Arterial	100.00
81	CA003814	WINNETKA AVE	2.145870	Urban Principal Arterial	100.00
82	CA006148	WINNETKA AVE	1.305920	Urban Principal Arterial	100.00
83	CA007083	WINNETKA AVE	1.717770	Urban Principal Arterial	100.00
84	CA008301	WINNETKA AVE	2.852830	Urban Principal Arterial	100.00
85	CA009129	WINNETKA AVE	1.817270	Urban Principal Arterial	100.00
86	CA003810	WOODLEY AVE	2.248690	Urban Principal Arterial	100.00
87	CA006145	WOODLEY AVE	1.637410	Urban Principal Arterial	100.00
88	CA006670	WOODLEY AVE	2.429660	Urban Principal Arterial	100.00
89	CA007081	WOODLEY AVE	1.637190	Urban Principal Arterial	100.00
90	CA016209	WOODLEY AVE	1.189580	Urban Principal Arterial	100.00
91	CA016210	WOODLEY AVE	1.242800	Urban Principal Arterial	100.00

Table 9: Functionality of bridges affected by Northridge earthquake

No.	Id	Name	Functionality at Day (%) …					
			1	3	7	14	30	90
1	CA022003	SR 118	59.20	62.90	67.90	68.90	70.20	79.20
2	CA022004	TAMPA AVE-W118 ON	61.30	65.00	69.90	70.90	72.10	80.70
3	CA022005	E118-TAMPA AVE OFF	61.30	65.00	69.90	70.90	72.10	80.70
4	CA022124	TAMPA AVE	68.20	71.50	76.10	76.90	77.90	85.20
5	CA023228	CORBIN AVE	74.40	80.10	83.50	84.10	84.90	90.60
6	CA023285	LASSEN ST	69.20	74.40	78.30	79.10	80.10	87.30
7	CA023303	NORDOFF ST	72.20	78.20	81.80	82.50	83.40	89.60
8	CA023305	NORDHOFF ST	76.20	84.50	87.70	88.30	88.80	93.00
9	CA023319	PARTHENIA ST	72.20	78.30	81.80	82.50	83.40	89.60
10	CA023323	HAYVENHURST ST	68.10	73.80	78.10	78.90	79.90	86.60
11	CA023324	PLUMMER ST	70.60	76.20	80.00	80.70	81.70	88.40
12	CA023327	RESEDA BLVD	71.40	77.20	80.90	81.60	82.50	88.90
13	CA023355	TAMPA AVE	71.70	77.60	81.30	82.00	82.90	89.20
14	CA023389	WILBUR AVE	66.30	70.60	74.70	75.60	76.70	84.80
15	CA023398	YOLANDA AVE	64.80	68.60	73.00	73.80	75.00	83.60
16	CA023686	NORDHOFF PLACE	75.30	80.80	84.10	84.80	85.50	91.00
17	CA023687	PRAIRIE ST	75.90	81.60	84.80	85.40	86.20	91.40
18	CA023688	HAYVENHURST AVE	78.60	81.40	84.70	85.30	86.10	91.40
19	CA023846	NORDHOFF WAY	70.50	73.70	78.00	78.90	79.80	86.50

As mentioned previously, the main objective of the models is to minimize the reconstruction time of a road infrastructure system affected by a disaster. Using Hazus and its simulation capability, we generated a list of essential facilities and bridges that would be damaged if there were an earthquake in Northridge, CA. The next step is to be able to find out the road infrastructure system that connects all of these essential facilities. Hazus did not provide the distance between the facilities affected. Hence, we decided to use Google maps.

6.1.2 Google maps data generation

Google maps was used to calculate the distance among the 33 facilities identified by Hazus. The criteria for calculating the distance was to pick the shortest paths. The reason for doing that is that the shortest paths are normally related to the main roads. These roads have the best maintenance and are the strongest in a road infrastructure system. This means that if they are damaged by a disaster, the secondary roads will be damaged too and probably more severely. Table 10 and Table 11 contain the shortest distance among the 33 facilities.

Table 10. Shortest paths (miles) between facilities in Northridge CA – part A

Roads	**ID**	**CA000037**	**CA003643**	**CA003644**	**CA003887**	**CA004228**	**CA005514**	**CA005515**	**CA005516**	**CA005517**	**CA005518**	**CA005519**	**CA005520**	**CA005528**	**CA008970**	**CA009964**	**CA010103**	**CA010337**
ID	**No.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
CA000037	1	0	2	1	2	2	3	3	1	2	2	4	3	4	1	1	4	3
CA003643	2	2	0	3	4	1	4	4	3	3	2	4	4	6	2	3	4	4
CA003644	3	1	3	0	1	2	2	2	1	3	2	4	3	3	2	1	3	2
CA003887	4	2	4	1	0	3	1	1	2	3	3	5	3	2	2	1	4	0.4
CA004228	5	2	1	2	3	0	3	3	2	1	1	2	3	5	1	2	3	3
CA005514	6	3	4	2	1	3	0	0.4	1	2	3	4	2	1	3	1	3	1
CA005515	7	3	4	2	1	3	0.4	0	1	2	3	4	2	1	3	2	3	0.5
CA005516	8	1	3	1	2	2	1	1	0	2	2	3	2	3	1	1	2	1
CA005517	9	2	3	3	3	1	2	2	2	0	1	2	2	3	1	2	2	3
CA005518	10	2	2	2	3	1	3	3	2	1	0	2	3	4	1	2	3	3
CA005519	11	4	4	4	5	2	4	4	3	2	2	0	2	4	3	4	1	4
CA005520	12	3	4	3	3	3	2	2	2	2	3	2	0	2	2	2	1	3
CA005528	13	4	6	3	2	5	1	1	3	3	4	4	2	0	4	3	2	1
CA008970	14	1	2	2	2	1	3	3	1	1	1	3	2	4	0	1	2	3
CA009964	15	1	3	1	1	2	1	2	1	2	2	4	2	3	1	0	3	1
CA010103	16	4	4	3	4	3	3	3	2	2	3	1	1	2	2	3	0	3
CA010337	17	3	4	2	0.4	3	1	0.5	1	3	3	4	3	1	3	1	3	0
CA010338	18	2	4	1	0.4	3	1	1	1	3	3	5	3	2	2	1	3	0.4
CA010339	19	1	3	1	2	2	1	1	0.1	2	2	3	2	3	1	1	2	1
CA010640	20	3	7	2	1	4	2	2	3	5	4	6	4	2	3	2	5	1
CA011783	21	2	3	3	3	2	2	2	2	1	2	2	1	3	1	2	1	3
CA012317	22	1	3	0.4	1	2	1	1	1	3	2	4	2	3	1	0.1	3	1
CA012393	23	4	4	5	5	2	4	4	4	2	3	1	3	4	3	4	2	5
CA012395	24	1	2	2	3	1	2	2	2	1	1	2	2	3	0.4	1	2	3
CA012500	25	1	3	2	2	1	3	3	1	1	1	3	2	4	0.4	1	2	3
CA012653	26	4	4	5	6	3	5	5	5	2	3	2	3	4	4	5	3	5
CA012654	27	4	5	2	2	4	1	1	2	3	4	3	2	0.4	3	2	2	1
CA012655	28	4	5	4	3	4	3	2	2	3	3	2	1	1	3	4	1	2
CA013049	29	2	1	3	4	2	4	4	3	3	2	4	4	5	2	3	4	4
CA001715	30	4	3	4	5	2	4	4	3	2	2	2	3	4	3	4	3	4
CA001718	31	4	4	5	5	2	4	4	3	2	2	2	3	4	3	4	3	4
CA001723	32	4	6	3	2	5	2	1	3	3	5	4	2	0.3	4	3	2	1
CA000019	33	3	4	3	4	3	3	3	2	1	2	2	1	2	2	3	1	3

Table 11. Shortest paths (miles) between facilities in Northridge CA –part B

Roads	**ID**	**CA010338**	**CA010339**	**CA010640**	**CA011783**	**CA012317**	**CA012393**	**CA012395**	**CA012500**	**CA012653**	**CA012654**	**CA012655**	**CA013049**	**CA001715**	**CA001718**	**CA001723**	**CA000019**
ID	**No.**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
CA000037	1	2	1	3	2	1	4	1	1	4	4	4	2	4	4	4	3
CA003643	2	4	3	7	3	3	4	2	3	4	5	5	1	3	4	6	4
CA003644	3	1	1	2	3	0.4	5	2	2	5	2	4	3	4	5	3	3
CA003887	4	0.4	2	1	3	1	5	3	2	6	2	3	4	5	5	2	4
CA004228	5	3	2	4	2	2	2	1	1	3	4	4	2	2	2	5	3
CA005514	6	1	1	2	2	1	4	2	3	5	1	3	4	4	4	2	3
CA005515	7	1	1	2	2	1	4	2	3	5	1	2	4	4	4	1	3
CA005516	8	1	0.1	3	2	1	4	2	1	5	2	2	3	3	3	3	2
CA005517	9	3	2	5	1	3	2	1	1	2	3	3	3	2	2	3	1
CA005518	10	3	2	4	2	2	3	1	1	3	4	3	2	2	2	5	2
CA005519	11	5	3	6	2	4	1	2	3	2	3	2	4	2	2	4	2
CA005520	12	3	2	4	1	2	3	2	2	3	2	1	4	3	3	2	1
CA005528	13	2	3	2	3	3	4	3	4	4	0.4	1	5	4	4	0.3	2
CA008970	14	2	1	3	1	1	3	0.4	0.4	4	3	3	2	3	3	4	2
CA009964	15	1	1	2	2	0.1	4	1	1	5	2	4	3	4	4	3	3
CA010103	16	3	2	5	1	3	2	2	2	3	2	1	4	3	3	2	1
CA010337	17	0.4	1	1	3	1	5	3	3	5	1	2	4	4	4	1	3
CA010338	18	0	1	2	3	1	5	3	2	6	2	3	4	4	4	2	3
CA010339	19	1	0	3	2	1	4	2	1	5	2	3	3	3	3	3	2
CA010640	20	2	3	0	4	2	6	4	3	7	3	4	5	6	6	3	5
CA011783	21	3	2	4	0	2	2	1	1	2	2	2	3	2	2	2	1
CA012317	22	1	1	2	2	0	4	2	1	5	2	4	3	4	4	3	3
CA012393	23	5	4	6	2	4	0	3	3	1	4	3	5	1	1	4	2
CA012395	24	3	2	4	1	2	3	0	0.4	3	3	3	3	2	2	3	1
CA012500	25	2	1	3	1	1	3	0.4	0	4	3	3	2	3	3	4	2
CA012653	26	6	5	7	2	5	1	3	4	0	4	3	5	1	1	5	3
CA012654	27	2	2	3	2	2	4	3	3	4	0	1	5	4	4	1	2
CA012655	28	3	3	4	2	4	3	3	3	3	1	0	5	4	4	1	1
CA013049	29	4	3	5	3	3	5	3	2	5	5	5	0	4	4	5	3
CA001715	30	4	3	6	2	4	1	2	3	1	4	4	4	0	0.3	5	3
CA001718	31	4	3	6	2	4	1	2	3	1	4	4	4	0.3	0	4	2
CA001723	32	2	3	3	2	3	4	3	4	5	1	1	5	5	4	0	3
CA000019	33	3	2	5	1	3	2	1	2	3	2	1	3	3	2	3	0

To be able to transform the distances to reconstruction times for each of the roads, we used the conclusion presented by Fritz and Noon (2017) “On a road construction project approximately three miles in length, it would take 79 working days to complete with technology versus 147 working days with traditional methods.” (Fritz and Noon. 2017, p 18). The reality is that the technology that is mentioned by Fritz and Noon (2017) is not available in all cases. Due to this, we decided to use, as a reference, the working time of 147 days per 3 miles of the traditional methods. Table 12 and Table 13 show the reconstruction time for the shortest paths of the roads, among essential facilities, as identified by Google maps. It is important to highlight that the bridges reconstruction time is calculated in the same way that the road reconstruction time.

Table 12. Reconstruction times of roads in Northridge CA – time (days) part A

Roads	**ID**	**CA000037**	**CA003643**	**CA003644**	**CA003887**	**CA004228**	**CA005514**	**CA005515**	**CA005516**	**CA005517**	**CA005518**	**CA005519**	**CA005520**	**CA005528**	**CA008970**	**CA009964**	**CA010103**	**CA010337**
ID	**No.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
CA000037	1	0	98	49	98	98	147	147	49	98	98	196	147	196	49	49	196	147
CA003643	2	98	0	147	196	49	196	196	147	147	98	196	196	294	98	147	196	196
CA003644	3	49	147	0	49	98	98	98	49	147	98	196	147	147	98	49	147	98
CA003887	4	98	196	49	0	147	49	49	98	147	147	245	147	98	98	49	196	20
CA004228	5	98	49	98	147	0	147	147	98	49	49	98	147	245	49	98	147	147
CA005514	6	147	196	98	49	147	0	20	49	98	147	196	98	49	147	49	147	49
CA005515	7	147	196	98	49	147	20	0	49	98	147	196	98	49	147	98	147	25
CA005516	8	49	147	49	98	98	49	49	0	98	98	147	98	147	49	49	98	49
CA005517	9	98	147	147	147	49	98	98	98	0	49	98	98	147	49	98	98	147
CA005518	10	98	98	98	147	49	147	147	98	49	0	98	147	196	49	98	147	147
CA005519	11	196	196	196	245	98	196	196	147	98	98	0	98	196	147	196	49	196
CA005520	12	147	196	147	147	147	98	98	98	98	147	98	0	98	98	98	49	147
CA005528	13	196	294	147	98	245	49	49	147	147	196	196	98	0	196	147	98	49
CA008970	14	49	98	98	98	49	147	147	49	49	49	147	98	196	0	49	98	147
CA009964	15	49	147	49	49	98	49	98	49	98	98	196	98	147	49	0	147	49
CA010103	16	196	196	147	196	147	147	147	98	98	147	49	49	98	98	147	0	147
CA010337	17	147	196	98	20	147	49	25	49	147	147	196	147	49	147	49	147	0
CA010338	18	98	196	49	20	147	49	49	49	147	147	245	147	98	98	49	147	20
CA010339	19	49	147	49	98	98	49	49	4.9	98	98	147	98	147	49	49	98	49
CA010640	20	147	343	98	49	196	98	98	147	245	196	294	196	98	147	98	245	49
CA011783	21	98	147	147	147	98	98	98	98	49	98	98	49	147	49	98	49	147
CA012317	22	49	147	20	49	98	49	49	49	147	98	196	98	147	49	4.9	147	49
CA012393	23	196	196	245	245	98	196	196	196	98	147	49	147	196	147	196	98	245
CA012395	24	49	98	98	147	49	98	98	98	49	49	98	98	147	20	49	98	147
CA012500	25	49	147	98	98	49	147	147	49	49	49	147	98	196	20	49	98	147
CA012653	26	196	196	245	294	147	245	245	245	98	147	98	147	196	196	245	147	245
CA012654	27	196	245	98	98	196	49	49	98	147	196	147	98	20	147	98	98	49
CA012655	28	196	245	196	147	196	147	98	98	147	147	98	49	49	147	196	49	98
CA013049	29	98	49	147	196	98	196	196	147	147	98	196	196	245	98	147	196	196
CA001715	30	196	147	196	245	98	196	196	147	98	98	98	147	196	147	196	147	196
CA001718	31	196	196	245	245	98	196	196	147	98	98	98	147	196	147	196	147	196
CA001723	32	196	294	147	98	245	98	49	147	147	245	196	98	15	196	147	98	49
CA000019	33	147	196	147	196	147	147	147	98	49	98	98	49	98	98	147	49	147

Table 13. Reconstruction times of roads in Northridge CA – time (days) Part B

Roads	**ID**	**CA010338**	**CA010339**	**CA010640**	**CA011783**	**CA012317**	**CA012393**	**CA012395**	**CA012500**	**CA012653**	**CA012654**	**CA012655**	**CA013049**	**CA001715**	**CA001718**	**CA001723**	**CA000019**
ID	**No.**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
CA000037	1	98	49	147	98	49	196	49	49	196	196	196	98	196	196	196	147
CA003643	2	196	147	343	147	147	196	98	147	196	245	245	49	147	196	294	196
CA003644	3	49	49	98	147	20	245	98	98	245	98	196	147	196	245	147	147
CA003887	4	20	98	49	147	49	245	147	98	294	98	147	196	245	245	98	196
CA004228	5	147	98	196	98	98	98	49	49	147	196	196	98	98	98	245	147
CA005514	6	49	49	98	98	49	196	98	147	245	49	147	196	196	196	98	147
CA005515	7	49	49	98	98	49	196	98	147	245	49	98	196	196	196	49	147
CA005516	8	49	4.9	147	98	49	196	98	49	245	98	98	147	147	147	147	98
CA005517	9	147	98	245	49	147	98	49	49	98	147	147	147	98	98	147	49
CA005518	10	147	98	196	98	98	147	49	49	147	196	147	98	98	98	245	98
CA005519	11	245	147	294	98	196	49	98	147	98	147	98	196	98	98	196	98
CA005520	12	147	98	196	49	98	147	98	98	147	98	49	196	147	147	98	49
CA005528	13	98	147	98	147	147	196	147	196	196	20	49	245	196	196	15	98
CA008970	14	98	49	147	49	49	147	20	20	196	147	147	98	147	147	196	98
CA009964	15	49	49	98	98	4.9	196	49	49	245	98	196	147	196	196	147	147
CA010103	16	147	98	245	49	147	98	98	98	147	98	49	196	147	147	98	49
CA010337	17	20	49	49	147	49	245	147	147	245	49	98	196	196	196	49	147
CA010338	18	0	49	98	147	49	245	147	98	294	98	147	196	196	196	98	147
CA010339	19	49	0	147	98	49	196	98	49	245	98	147	147	147	147	147	98
CA010640	20	98	147	0	196	98	294	196	147	343	147	196	245	294	294	147	245
CA011783	21	147	98	196	0	98	98	49	49	98	98	98	147	98	98	98	49
CA012317	22	49	49	98	98	0	196	98	49	245	98	196	147	196	196	147	147
CA012393	23	245	196	294	98	196	0	147	147	49	196	147	245	49	49	196	98
CA012395	24	147	98	196	49	98	147	0	20	147	147	147	147	98	98	147	49
CA012500	25	98	49	147	49	49	147	20	0	196	147	147	98	147	147	196	98
CA012653	26	294	245	343	98	245	49	147	196	0	196	147	245	49	49	245	147
CA012654	27	98	98	147	98	98	196	147	147	196	0	49	245	196	196	49	98
CA012655	28	147	147	196	98	196	147	147	147	147	49	0	245	196	196	49	49
CA013049	29	196	147	245	147	147	245	147	98	245	245	245	0	196	196	245	147
CA001715	30	196	147	294	98	196	49	98	147	49	196	196	196	0	15	245	147
CA001718	31	196	147	294	98	196	49	98	147	49	196	196	196	15	0	196	98
CA001723	32	98	147	147	98	147	196	147	196	245	49	49	245	245	196	0	147
CA000019	33	147	98	245	49	147	98	49	98	147	98	49	147	147	98	147	0

While computing the distances among the essential facilities, we also identified when a damaged bridge(s) was(were) part of the shortest path. Table 14 presents when a damaged bridge is part of the shortest path that connects two essential facilities.

Table 14. Damaged bridges part of the shortest paths in Northridge CA

Road between facilities	Uses Bridge ID																		
	CA022003	**CA022004**	**CA022005**	**CA022124**	**CA023228**	**CA023285**	**CA023303**	**CA023305**	**CA023319**	**CA023323**	**CA023324**	**CA023327**	**CA023355**	**CA023389**	**CA023398**	**CA023686**	**CA023687**	**CA023688**	**CA023846**
CA004228-CA000037						1		1				1							
CA005517-CA000037						1						1							
								.											
								.											
								.											

The complete can be seen in Appendix 1.

The reconstruction time of a bridge was estimated by two different methods. The first one was assuming that Fritz and Noon (2017) conclusion can be applied for the reconstruction of a bridge. The second one was using the information presented in Table 9: Functionality of bridges affected by Northridge earthquake. The details of these two approaches and how they were used in the numerical experiments will be presented in the following section.

Having the reconstruction times for the road infrastructure system that connects all the essential facilities that would be affected by a Northridge, CA earthquake is the last step in collecting the data. The next step is organizing it so that it can be used in the Steiner Tree and scheduling models.

6.2 Getting data ready for Steiner Tree and Scheduling models

With the objective of making the identification of the Northridge, CA essential facilities and bridges easier, we decided to do a one-to-one mapping. Table 15 and Table 16 show the ID nodes assigned to each facility and bridge in the network representation.

Table 15. ID nodes for Northridge, CA facilities

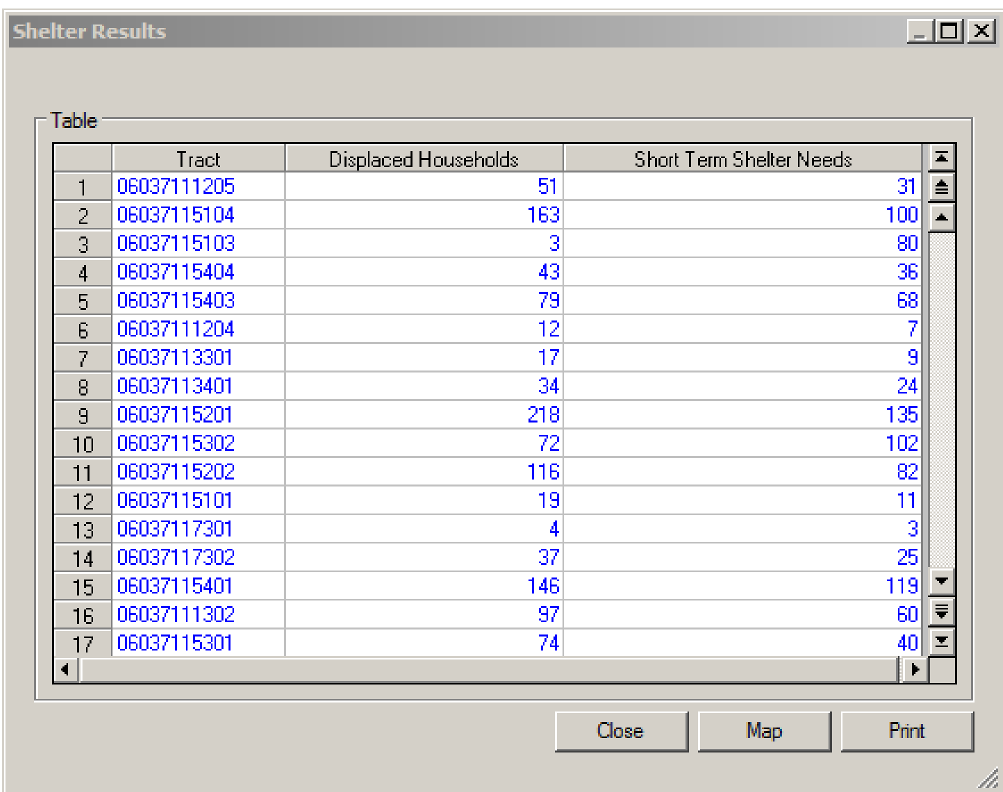
Type	Hazus ID	Name	ID Node
Police Station	CA000037	Los Angeles Police Dept	1
School	CA003643	Beckford Avenue Elementary	2
School	CA003644	Andasol Avenue Elementary	3
School	CA003887	Balboa Gifted/High Ability Magnet Elemen	4
School	CA004228	Alfred Bernhard Nobel Middle	5
School	CA005514	Dearborn Street Elementary	6
School	CA005515	Oliver Wendell Holmes Middle	7
School	CA005516	Northridge Academy High	8
School	CA005517	Calahan Street Elementary	9
School	CA005518	Topeka Drive Elementary	10
School	CA005519	Napa Street Elementary	11
School	CA005520	Northridge Middle	12
School	CA005528	Parthenia Street Elementary	13
School	CA008970	Our Lady of Lourdes School	14
School	CA009964	Casa Montessori	15
School	CA010103	First Lutheran Elementary School	16
School	CA010337	St Nicholas School	17
School	CA010338	Highland Hall Waldorf School	18
School	CA010339	Northpoint School	19
School	CA010640	Los Angeles Baptist Hs	20
School	CA011783	Countryside Preparatory School	21
School	CA012317	San Fernando Valley Academy	22
School	CA012393	Kidsville Usa	23
School	CA012395	Abc Educational Center	24
School	CA012500	Child & Family Studies Center	25
School	CA012653	Our Redeemer Lutheran School	26
School	CA012654	Knollwood Pre School & Kgn	27
School	CA012655	Pinecrest School-Whiteoak	28
School	CA013049	New World Moutessori School	29
Hazardous Materials	CA001715	Micro Matic Usa Inc.	30
Hazardous Materials	CA001718	3m Pharmaceuticals	31
Hazardous Materials	CA001723	Harman Motive Inc.	32
BUS	CA000019	R & D Transportation Svc	33

Table 16. ID node for Northridge, CA bridges

Hazus ID	Name	ID Node
CA022003	SR 118	B1
CA022004	TAMPA AVE-W118 ON	B2
CA022005	E118-TAMPA AVE OFF	B3
CA022124	TAMPA AVE	B4

Hazus ID	Name	ID Node
CA023228	CORBIN AVE	B5
CA023285	LASSEN ST	B6
CA023303	NORDOFF ST	B7
CA023305	NORDHOFF ST	B8
CA023319	PARTHENIA ST	B9
CA023323	HAYVENHURST ST	B10
CA023324	PLUMMER ST	B11
CA023327	RESEDA BLVD	B12
CA023355	TAMPA AVE	B13
CA023389	WILBUR AVE	B14
CA023398	YOLANDA AVE	B15
CA023686	NORDHOFF PLACE	B16
CA023687	PRAIRIE ST	B17
CA023688	HAYVENHURST AVE	B18
CA023846	NORDHOFF WAY	B19

The next step was to identify the shelters' locations. To do that we used the shelter requirements provided by Hazus. This information can be seen in Figure 41.



	Tract	Displaced Households	Short Term Shelter Needs
1	06037111205	51	31
2	06037115104	163	100
3	06037115103	3	80
4	06037115404	43	36
5	06037115403	79	68
6	06037111204	12	7
7	06037113301	17	9
8	06037113401	34	24
9	06037115201	218	135
10	06037115302	72	102
11	06037115202	116	82
12	06037115101	19	11
13	06037117301	4	3
14	06037117302	37	25
15	06037115401	146	119
16	06037111302	97	60
17	06037115301	74	40

Figure 41. Shelter requirements

Unfortunately, Hazus did not provide the information of the existing shelters in the Northridge, CA area. Hence, we decided to designate some schools as shelters. We selected schools that are located in the same tract number where shelters are needed. We also confirmed that schools have enough capacity to satisfy the shelters' requirements.

Table 17 shows that only in three cases there were no schools in the location where there was a shelter requirement. However, as can be seen in Figure 42, every geographic area has a school-shelter that can be accessed.

Table 17. Shelters vs schools

Shelters' Requirements		**Selected Schools**	
Tract	**Short Term Shelter Needs**	**Tract**	**Capacity**
06037111205	31	None	
06037115104	100	06037115104	805
06037115103	80	06037115103	18
06037115404	36	None	
06037115403	68	06037115403	138
06037111204	7	06037111204	574
06037113301	9	None	
06037113401	24	06037113401	48
06037115201	135	06037115201	309
06037115302	102	06037115302	725
06037115202	82	06037115202	465
06037115101	11	06037115101	659
06037117301	3	06037117301	983
06037117302	25	06037117302	796
06037115401	119	06037115401	1153
06037111302	60	06037111302	529
06037115301	40	06037115301	542
Total	**932**	**Total**	**7744**

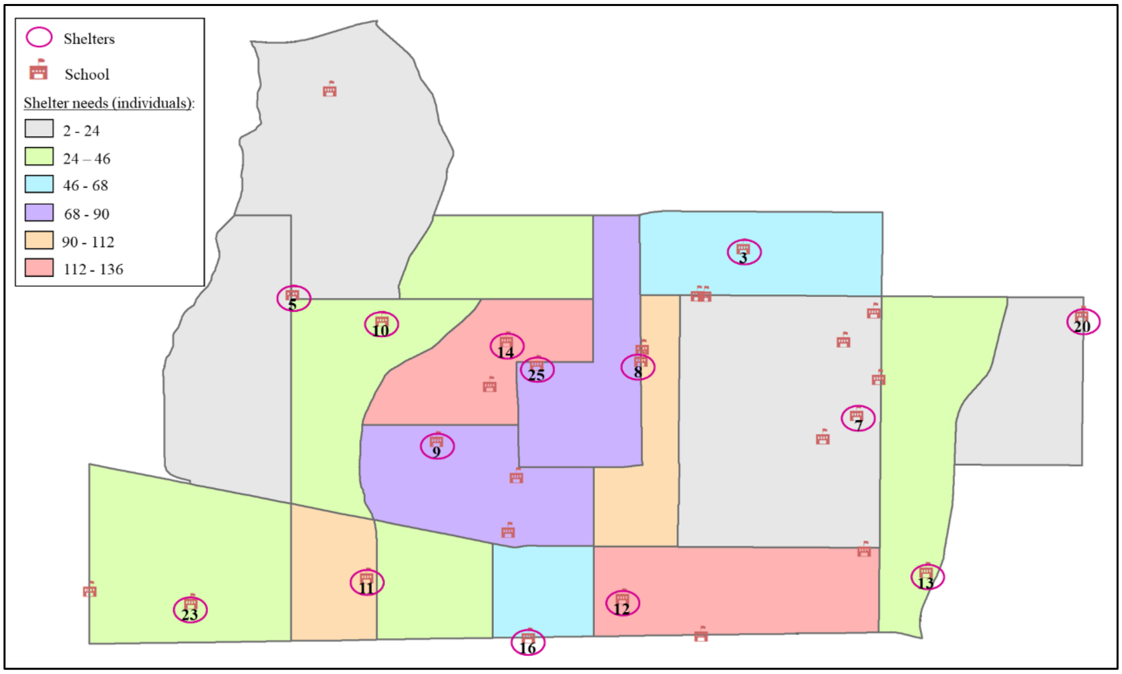


Figure 42. Shelters' requirements and locations

Table 18 shows the list of schools that were selected as shelters.

Table 18. Northridge CA shelters

Hazus ID	Name	ID Node
CA004228	ALFRED BERNHARD NOBEL MIDDLE	5
CA003644	ANDASOL AVENUE ELEMENTARY	3
CA012393	KIDSVILLE USA	23
CA005515	OLIVER WENDELL HOLMES MIDDLE	7
CA012500	CHILD & FAMILY STUDIES CENTER	25
CA005516	NORTHRIDGE ACADEMY HIGH	8
CA008970	OUR LADY OF LOURDES SCHOOL	14
CA005517	CALAHAN STREET ELEMENTARY	9
CA005518	TOPEKA DRIVE ELEMENTARY	10
CA005519	NAPA STREET ELEMENTARY	11
CA005520	NORTHRIDGE MIDDLE	12
CA010103	FIRST LUTHERAN ELEMENTARY SCHOOL	16
CA010640	LOS ANGELES BAPTIST HS	20
CA005528	PARTHENIA STREET ELEMENTARY	13

The last piece of information that we needed before applying our methodology is related to the priority and interdependency groups as well as the location of the crews. Unfortunately, it was not possible to collect real information regarding the priority groups and interdependencies as well as crews' locations for the Northridge, CA area. Hence, we created the priority groups which are presented in Table 19 and the interdependency groups seen in Table 20 in an arbitrary way. Regarding the crew's location, we decided that if there was a single crew it would be located in the vicinity of the police department. In case there was more than one crew, we would locate them in an arbitrary way. In our numerical experiments, we developed one scenario with one crew and another one with two crews. The crews' locations are presented in Table 21. It is important to highlight that our methodology does not depend on the locations of any of the essential facilities or crews.

Table 19. Priority groups

Priority groups	**Hazus ID**	**Type**	**Name**	**ID Node**
Priority 1	CA000037	Police	LOS ANGELES POLICE DEPT	1
	CA000019	BUS	R & D TRANSPORTATION SVC	33
Priority 2	CA003643	Schools	BECKFORD AVENUE ELEMENTARY	2
	CA009964		CASA MONTESSORI	15
	CA012317		SAN FERNANDO VALLEY ACADEMY	22
	CA012653		OUR REDEEMER LUTHERAN SCHOOL	26
	CA003887		BALBOA GIFTED/HIGH ABILITY MAGNET ELEMEN	4
	CA005514		DEARBORN STREET ELEMENTARY	6
Priority 3	CA000037	Police	LOS ANGELES POLICE DEPT	1
	CA001715	Hazmat	MICRO MATIC USA INC.	30
	CA001718		3M PHARMACEUTICALS	31
	CA001723		HARMAN MOTIVE INC.	32
Non priority	CA010337	Schools	ST NICHOLAS SCHOOL	17
	CA010338		HIGHLAND HALL WALDORF SCHOOL	18
	CA010339		NORTHPOINT SCHOOL	19
	CA012395		ABC EDUCATIONAL CENTER	24
	CA011783		COUNTRYSIDE PREPARATORY SCHOOL	21
	CA013049		NEW WORLD MOUTESSORI SCHOOL	29
	CA012654		KNOLLWOOD PRE SCHOOL & KGN	27
	CA012655		PINECREST SCHOOL-WHITEOAK	28

Table 20. Interdependency groups

Interdependency groups	**Hazus ID**	**Type**	**Name**	**ID Node**
Group 1	CA003887	School	BALBOA GIFTED/HIGH ABILITY MAGNET ELEMEN	4
	CA010338	School	HIGHLAND HALL WALDORF SCHOOL	18
Group 2	CA003643	School	BECKFORD AVENUE ELEMENTARY	2
	CA012653	School	OUR REDEEMER LUTHERAN SCHOOL	26

Table 21. Crews' locations

Crew number	**Hazus ID**	**Type**	**ID Node**
1	CA000037	Police	1
2	CA005528	School/Shelter	13

As it was mentioned before, the reconstruction time of a bridge was estimated by two different methods. The first one was assuming that Fritz and Noon (2017) conclusion can be applied for the reconstruction of a bridge. The second one was using the information presented in Table 9 on the functionality of bridges affected by Northridge Earthquake. As it can be seen in Table 9, 90 days after the disaster, the maximum functionality value that a bridge can get is 93%. As a result, we decided to estimate the reconstruction time based on getting all the bridges affected by the earthquake to a functionality value of 93%. To do that, we observed the data and concluded that after 7 days there is a linear relationship between functionally and days. So, we developed a linear equation for all the bridges and used that equation to predict the reconstruction time. Figure 43 shows the linear equation for bridge B1. The detailed information for all the bridges can be seen in (Appendix 2).

Table 22 contains the predicted reconstruction times for all the bridges affected by the Northridge, CA earthquake.

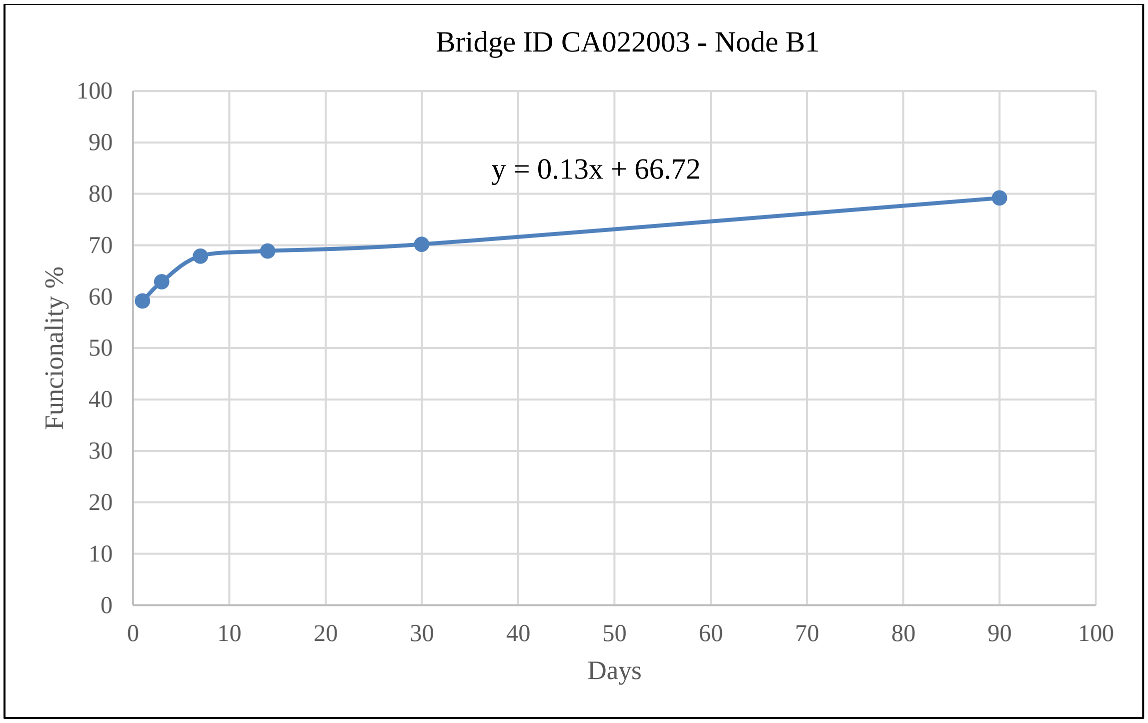


Figure 43. Bridge B1 linear equation for reconstruction time

Table 22. Reconstruction time (days) – 93% Functionality

Hazus ID	**93% Functionality**	**ID Node**
CA022003	191.90	B1
CA022004	185.27	B2
CA022005	185.27	B3
CA022124	161.88	B4
A023228	119.03	B5
CA023285	143.43	B6
CA023303	127.09	B7
CA023305	91.11	B8
CA023319	127.09	B9
CA023323	153.34	B10
CA023324	136.21	B11
CA023327	133.43	B12
CA023355	130.82	B13
CA023389	158.18	B14
CA023398	163.99	B15
CA023686	115.20	B16
CA023687	111.04	B17
CA023688	110.76	B18
CA023846	154.65	B19

Table 23 and Table 24 show the reconstruction times for the shortest paths of the roads including the predicted bridges' reconstruction times (Table 22) among essential facilities.

Table 23. Reconstruction times of roads and bridges (93% functionality) – time (days) part A

Roads	**ID**	**CA000037**	**CA003643**	**CA003644**	**CA003887**	**CA004228**	**CA005514**	**CA005515**	**CA005516**	**CA005517**	**CA005518**	**CA005519**	**CA005520**	**CA005528**	**CA008970**	**CA009964**	**CA010103**	**CA010337**
ID	**No.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
CA000037	1	0	98	49	98	235	147	147	49	143	98	316	147	196	143	49	196	147
CA003643	2	98	0	147	196	49	196	196	147	158	98	196	196	294	98	147	196	196
CA003644	3	49	147	0	49	98	98	98	49	249	98	222	147	147	98	49	147	98
CA003887	4	98	196	49	0	147	49	49	98	147	147	245	147	98	98	49	196	20
CA004228	5	235	49	98	147	0	147	147	98	49	49	371	158	245	91	98	158	147
CA005514	6	147	196	98	49	147	0	20	49	98	147	196	98	49	147	49	147	49
CA005515	7	147	196	98	49	147	20	0	49	98	147	196	98	49	147	98	147	25
CA005516	8	49	147	49	98	98	49	49	0	98	98	147	98	147	49	49	98	49
CA005517	9	143	158	249	147	49	98	98	98	0	158	258	98	147	49	249	98	147
CA005518	10	98	98	98	147	49	147	147	98	158	0	416	158	196	91	98	158	147
CA005519	11	316	196	222	245	371	196	196	147	258	416	0	98	196	267	222	49	196
CA005520	12	147	196	147	147	158	98	98	98	98	158	98	0	98	98	98	49	147
CA005528	13	196	294	147	98	245	49	49	147	147	196	196	98	0	196	147	98	49
CA008970	14	143	98	98	98	91	147	147	49	49	91	267	98	196	0	49	98	147
CA009964	15	49	147	49	49	98	49	98	49	249	98	222	98	147	49	0	147	49
CA010103	16	196	196	147	196	158	147	147	98	98	158	49	49	98	98	147	0	147
CA010337	17	147	196	98	20	147	49	25	49	147	147	196	147	49	147	49	147	0
CA010338	18	98	196	49	20	147	49	49	49	147	147	245	147	98	98	49	147	20
CA010339	19	49	147	49	98	98	49	49	5	98	98	147	98	147	49	49	98	49
CA010640	20	147	343	98	49	196	153	153	153	249	196	294	196	98	147	98	245	153
CA011783	21	143	158	147	147	158	98	98	98	49	158	127	49	147	49	98	49	147
CA012317	22	49	147	20	49	98	49	49	49	249	98	222	98	147	49	5	147	49
CA012393	23	196	196	245	245	98	196	196	282	282	440	49	147	196	255	210	98	245
CA012395	24	143	158	98	147	158	98	98	98	49	158	267	98	147	20	49	98	147
CA012500	25	49	147	98	98	91	147	147	49	49	91	267	98	196	20	49	98	147
CA012653	26	196	196	245	294	147	245	245	245	282	294	98	147	196	196	245	147	245
CA012654	27	196	245	98	98	196	49	49	98	147	196	147	98	20	147	98	98	49
CA012655	28	196	245	196	147	196	147	98	98	147	158	98	49	49	147	196	49	98
CA013049	29	98	192	147	277	192	196	277	147	350	192	617	277	277	277	277	277	277
CA001715	30	196	147	210	282	98	282	282	282	282	440	98	147	196	282	210	147	282
CA001718	31	196	196	245	282	98	282	282	282	282	440	98	147	196	282	210	147	282

Roads	ID	CA000037	CA003643	CA003644	CA003887	CA004228	CA005514	CA005515	CA005516	CA005517	CA005518	CA005519	CA005520	CA005528	CA008970	CA009964	CA010103	CA010337
ID	**No.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
CA001723	32	196	294	147	98	245	98	49	147	147	245	196	98	15	196	147	98	49
CA000019	33	147	196	147	196	158	147	147	98	49	158	98	49	98	98	147	49	147

Table 24. Reconstruction times of roads and bridges (93% functionality) – time (days) part B

Roads	ID	CA010338	CA010339	CA010640	CA011783	CA012317	CA012393	CA012395	CA012500	CA012653	CA012654	CA012655	CA013049	CA001715	CA001718	CA001723	CA000019
ID	**No.**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
CA000037	1	98	49	147	143	49	196	143	49	196	196	196	98	196	196	196	147
CA003643	2	196	147	343	158	147	196	158	147	196	245	245	192	147	196	294	196
CA003644	3	49	49	98	147	20	245	98	98	245	98	196	147	210	245	147	147
CA003887	4	20	98	49	147	49	245	147	98	294	98	147	277	282	282	98	196
CA004228	5	147	98	196	158	98	98	158	91	147	196	196	192	98	98	245	158
CA005514	6	49	49	153	98	49	196	98	147	245	49	147	196	282	282	98	147
CA005515	7	49	49	153	98	49	196	98	147	245	49	98	277	282	282	49	147
CA005516	8	49	5	153	98	49	282	98	49	245	98	98	147	282	282	147	98
CA005517	9	147	98	249	49	249	282	49	49	282	147	147	350	282	282	147	49
CA005518	10	147	98	196	158	98	440	158	91	294	196	158	192	440	440	245	158
CA005519	11	245	147	294	127	222	49	267	267	98	147	98	617	98	98	196	98
CA005520	12	147	98	196	49	98	147	98	98	147	98	49	277	147	147	98	49
CA005528	13	98	147	98	147	147	196	147	196	196	20	49	277	196	196	15	98
CA008970	14	98	49	147	49	49	255	20	20	196	147	147	277	282	282	196	98
CA009964	15	49	49	98	98	5	210	49	49	245	98	196	277	210	210	147	147
CA010103	16	147	98	245	49	147	98	98	98	147	98	49	277	147	147	98	49
CA010337	17	20	49	153	147	49	245	147	147	245	49	98	277	282	282	49	147
CA010338	18	0	49	98	147	49	245	147	98	294	98	147	277	282	282	98	147
CA010339	19	49	0	147	98	49	282	98	49	245	98	147	147	282	282	147	98
CA010640	20	98	147	0	196	98	294	196	147	343	147	196	245	294	294	147	245
CA011783	21	147	98	196	0	98	127	49	49	127	98	98	277	282	282	98	49
CA012317	22	49	49	98	98	0	210	98	49	245	98	196	277	210	210	147	147
CA012393	23	245	282	294	127	210	0	255	255	49	196	147	311	49	49	196	127
CA012395	24	147	98	196	49	98	255	0	20	147	147	147	350	282	282	147	49
CA012500	25	98	49	147	49	49	255	20	0	196	147	147	277	282	282	196	98
CA012653	26	294	245	343	127	245	49	147	196	0	196	147	245	49	49	245	147
CA012654	27	98	98	147	98	98	196	147	147	196	0	49	277	196	196	49	98
CA012655	28	147	147	196	98	196	147	147	147	147	49	0	277	196	196	49	49
CA013049	29	277	147	245	277	277	311	350	277	245	277	277	0	311	311	245	277

Roads	ID	CA010338	CA010339	CA010640	CA011783	CA012317	CA012393	CA012395	CA012500	CA012653	CA012654	CA012655	CA013049	CA001715	CA001718	CA001723	CA000019
ID	**No.**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
CA001715	30	282	282	294	282	210	49	282	282	49	196	196	311	0	15	245	147
CA001718	31	282	282	294	282	210	49	282	282	49	196	196	311	15	0	196	127
CA001723	32	98	147	147	98	147	196	147	196	245	49	49	245	245	196	0	147
CA000019	33	147	98	245	49	147	127	49	98	147	98	49	277	147	127	147	0

Finally, we have all the information for running the numerical experiments. In the next section, we present different scenarios that allowed us to test our methodology and the scalability of our models.

6.3 Scenarios for Numerical Experimentation

In this section, we present our numerical results for 5 different scenarios.

1. *Worst case:* In this scenario, the entire road infrastructure system was damaged by the disaster. In other words, there is not a single road or bridge in working condition. In this scenario, we also assumed that the bridges' reconstruction time is the same as the highway reconstruction time.

   As mentioned in Section 5.5.2, we developed two different formulations for the scheduling model. In order to be able to show the application of both formulations, we decided to apply both in this scenario.

   a. Worst case - single crew

   b. Worst case – multiple crews.

2. *Only bridges:* As it was presented in Table 8 no highways were affected according to the Hazus simulation result. However, 19 bridges were damaged by the earthquake. Due to this, we decided to create a scenario that reflected that situation. In other words, in this

scenario only the bridges were damaged. It means that only 42% of the road infrastructure was damaged by the earthquake. In addition, we used the predicted bridges' reconstruction time that was presented in Table 23 and Table 24 instead of the highway reconstruction time.

3. *Bridges and 50% of the remaining roads:* In this scenario we are assuming that all bridges and 50% of the roads that do not have bridges on them were damaged. This means that 71% of the road infrastructure was damaged by the earthquake.

4. *90%:* In this scenario 90% of the roads including those that have bridges on them were damaged.

6.3.1 Northridge, CA Worst Case – Single Crew

Using the information presented in the above section, we represented the worst case scenario as can be seen in Figure 44. The infrastructure system includes 33 essential facilities, 528 bidirectional roads that could be restored, 1 crew, 3 priority groups, and 2 interdependency groups.

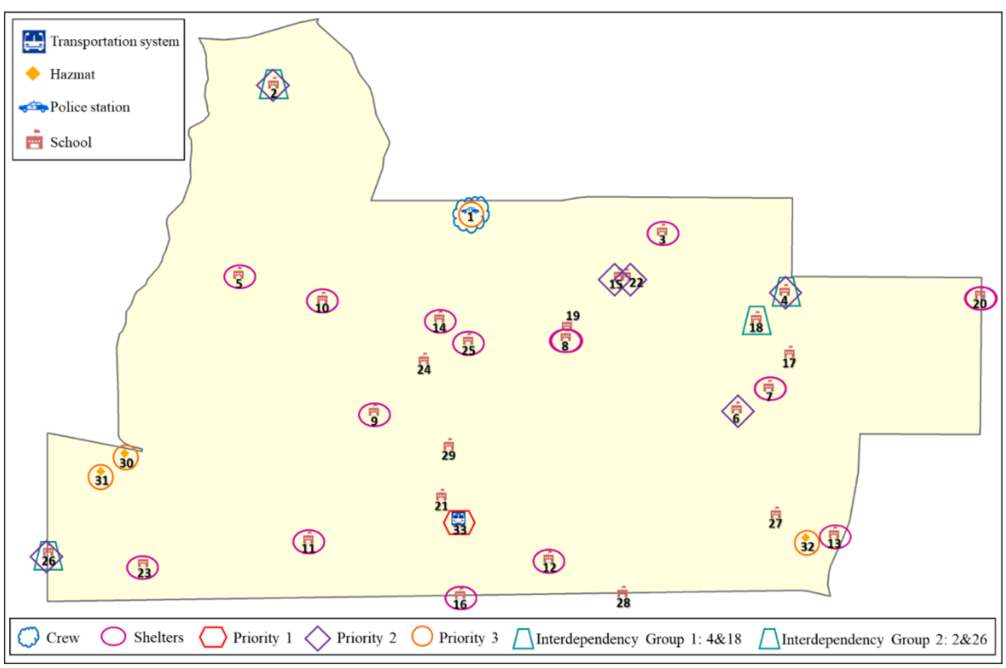


Figure 44. Illustration of road infrastructure system after an earthquake strikes – worst case – single crew

The first step is to solve the problem for the priority 1 group essential facilities. The infrastructure system that needs to be addressed in this priority group is presented in Figure 45.

As it was established in our methodology, we applied the Steiner tree model for identifying the list of roads that needed to be fixed. These roads provide connections to shelters, crew, and essential facilities listed in priority 1. Figure 46 represents the Steiner tree solution. This solution identified 16 roads that needed to be fixed. Analyzing the Steiner tree solution, we were able to conclude that none of the facilities that are part of the interdependency groups was included in the solution.

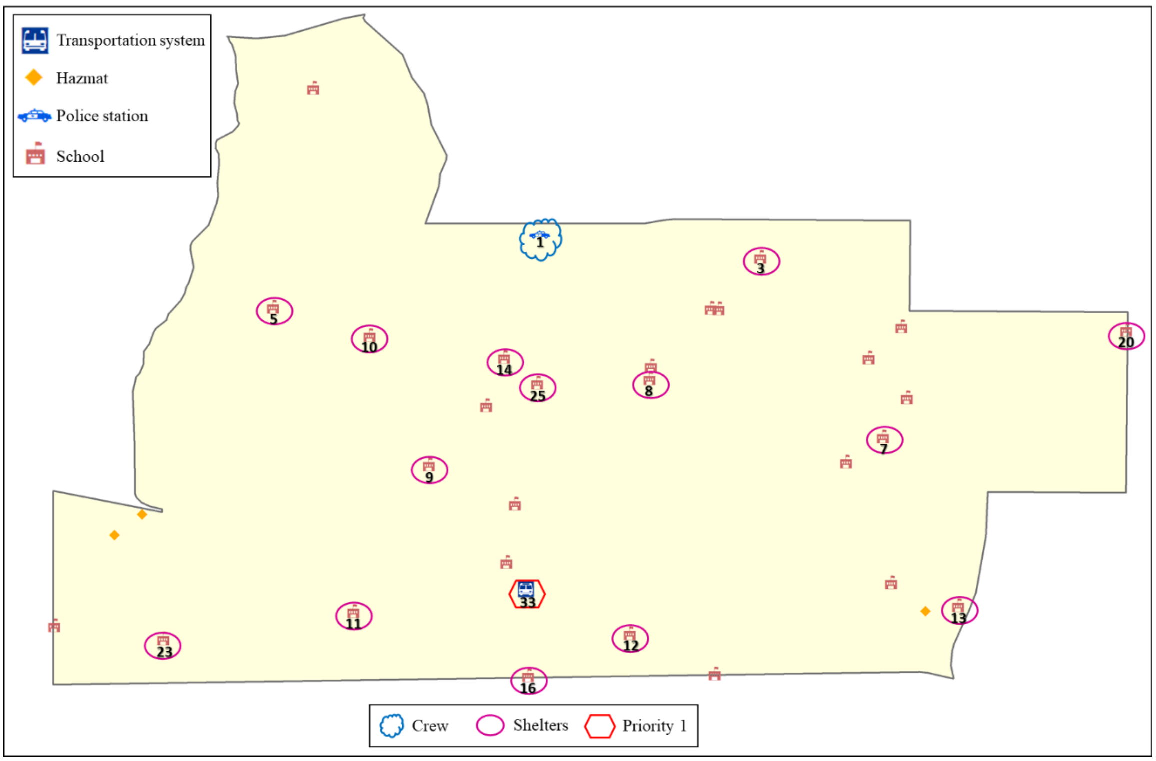


Figure 45. Initial road system for priority 1 - worst case – single crew

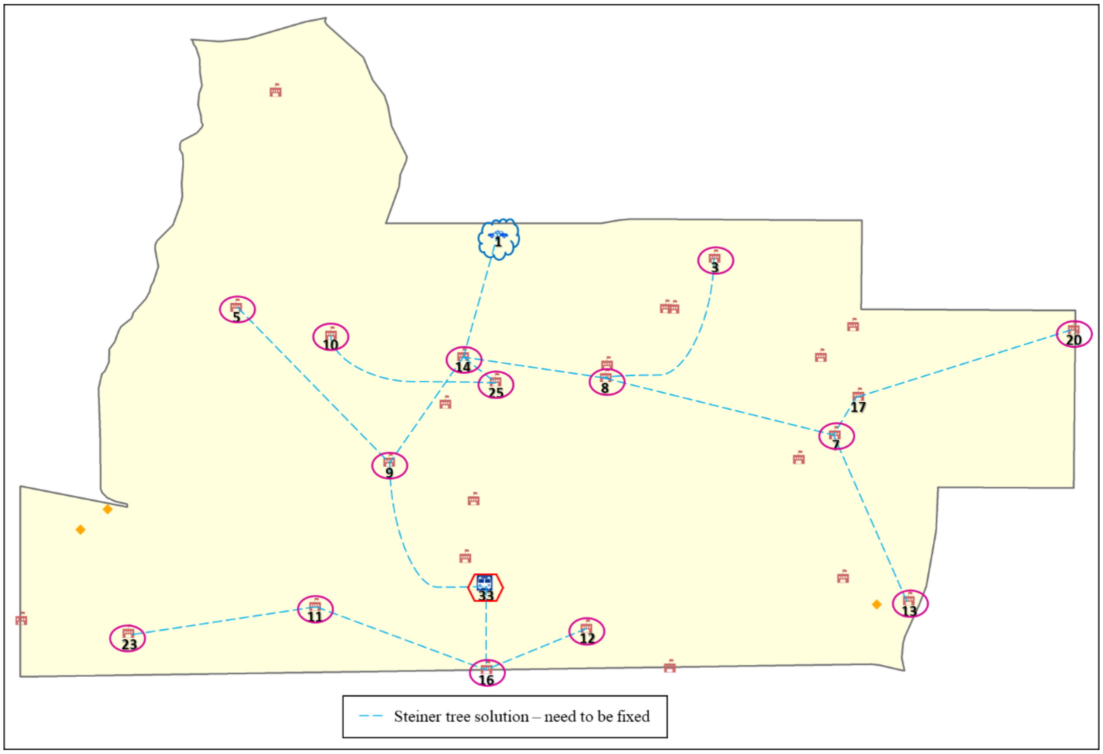


Figure 46. Steiner tree solution for priority 1 - worst case – single crew

The next step is to do a one-to-one mapping between roads and jobs (see Figure 47). Applying the scheduling formulation, we obtained the crew schedule which is presented in Figure 48.

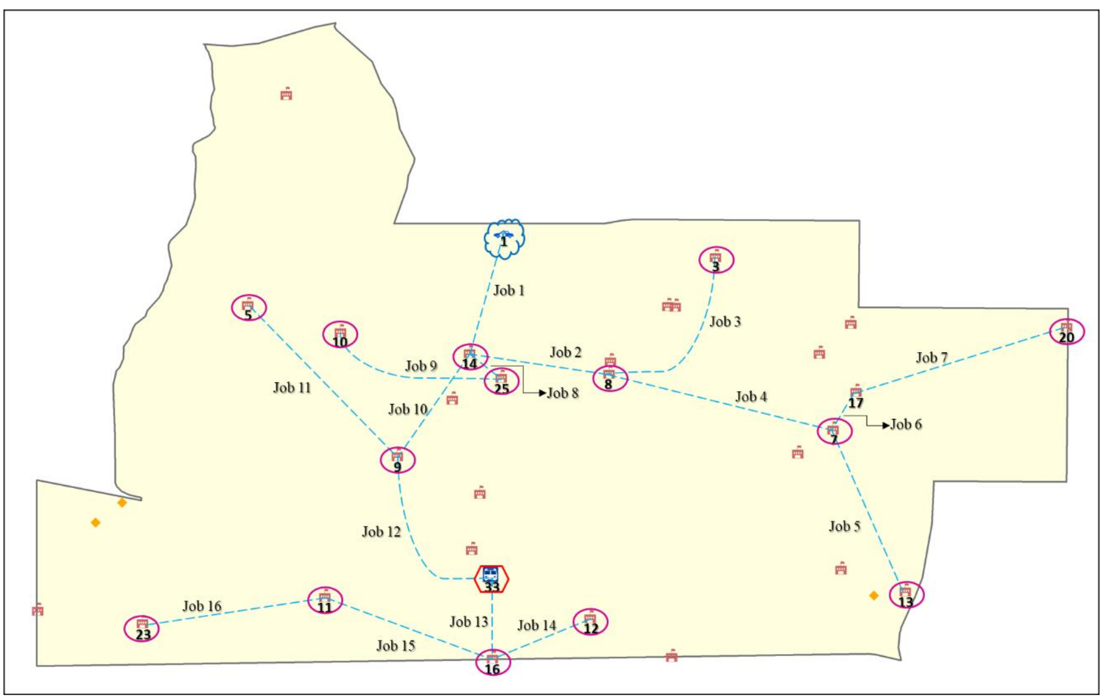


Figure 47. Jobs to schedule for priority 1 - worst case – single crew

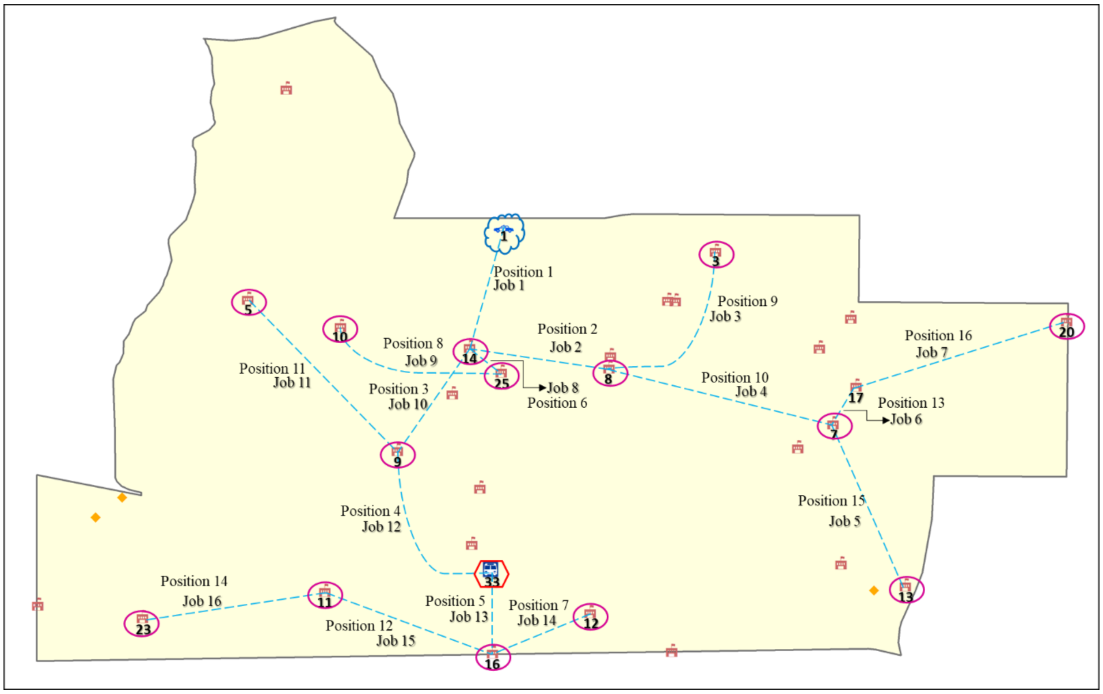


Figure 48. Crew's schedule for priority 1 - worst case – single crew

Figure 49 presents the restored infrastructure system that connects all the essential facilities and shelters for the priority 1 group.

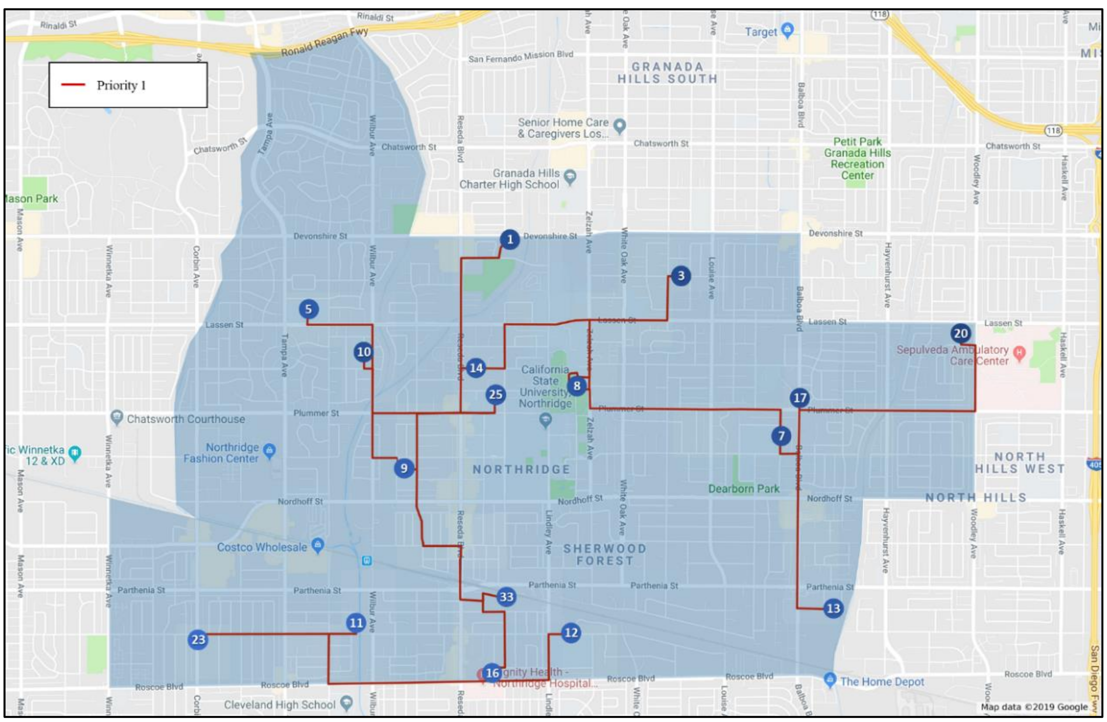


Figure 49. Restored road infrastructure system priority 1 - worst case – single crew

As the last step, we updated the road infrastructure system with the restored roads and indicated the new initial position of the crew. It is important to highlight that the crew location for priority 2 depends on the last job that was done in priority 1. This information is considered as the initial road infrastructure system for solving the priority 2 group requirements. A representation of the updated system is presented in Figure 50.

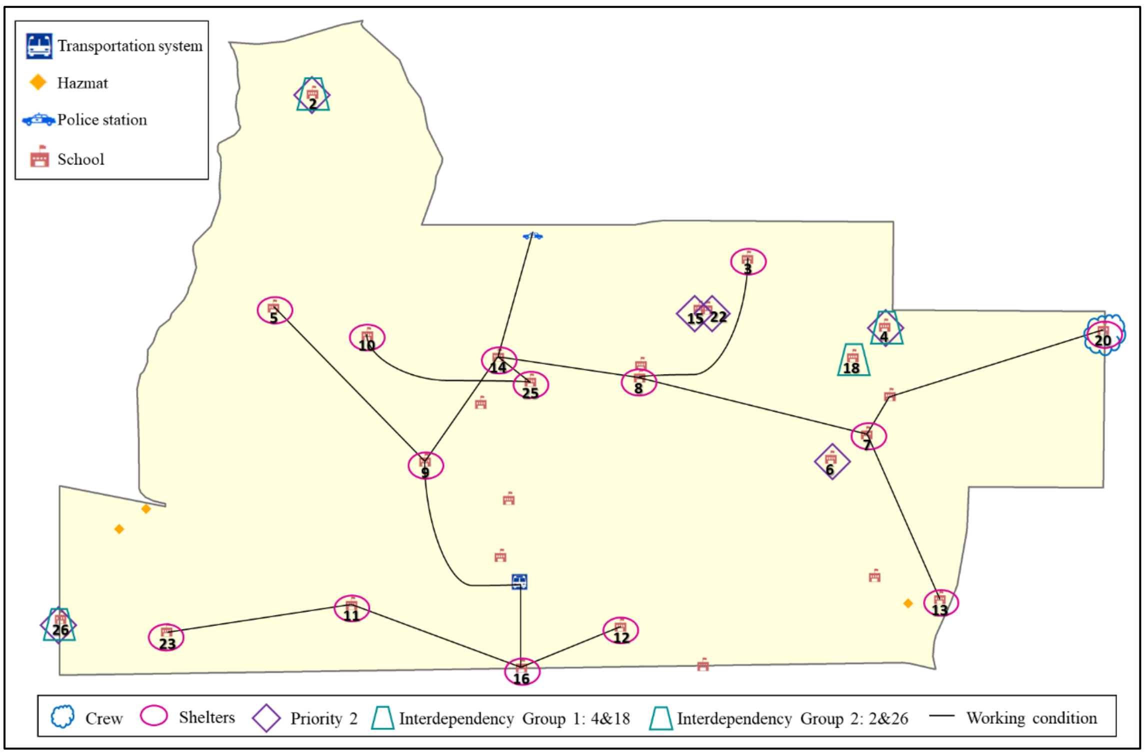


Figure 50. Initial road system for priority 2 - worst case – single crew

As can be seen in Figure 51 the Steiner tree model's solution uses 15 of the 16 roads that are in working condition. In addition, the model identified 6 new roads that need to be fixed.

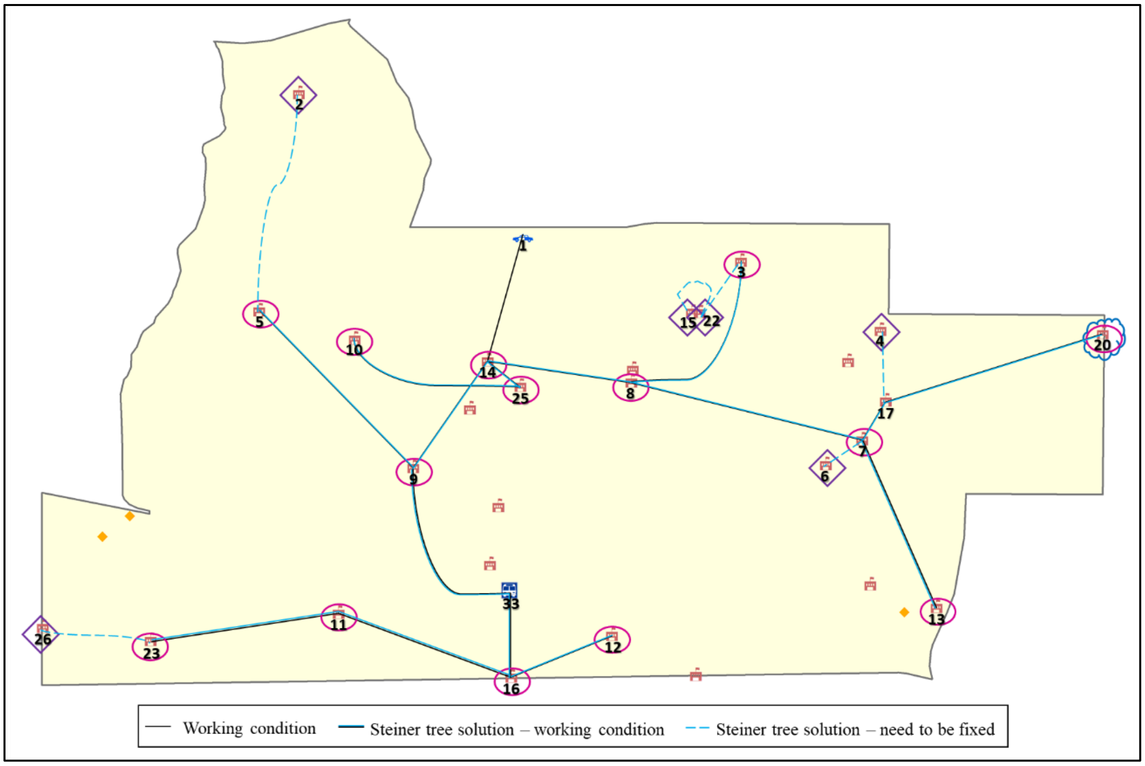


Figure 51. Steiner tree solution for priority 2 - worst case – single crew

Before we moved to the scheduling model, it was necessary to check if any of the facilities that have an interdependency was included in the Steiner tree solution. Both interdependency groups were included in the priority 2 solution. The 2 facilities (2 and 26) that are part of the interdependency group 2 were part of the solution. However, just 1 of the 2 facilities (4 and 18) in the interdependency group 1 was included. Due to this situation, it was necessary to rerun the Steiner tree model including facility 18 as part of priority 2 group. The updated Steiner tree solution is presented in Figure 52. Instead of having to fix 6 roads, now we must fix 7 roads.

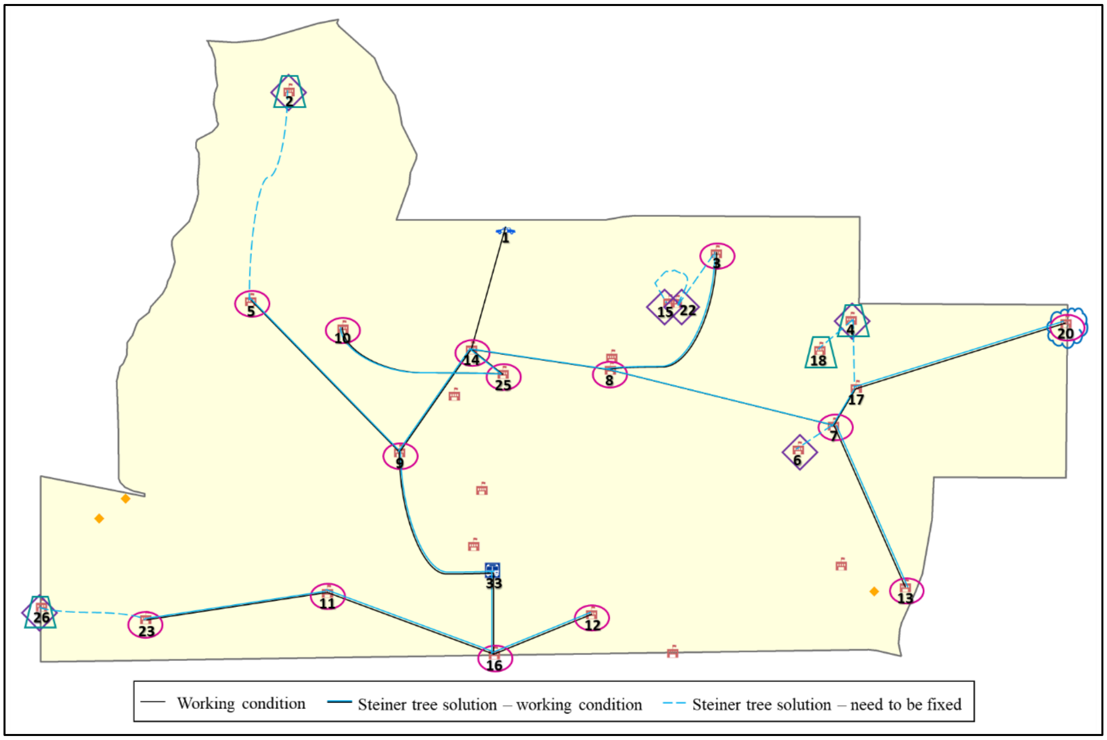


Figure 52. Steiner tree solution for priority 2 with interdependencies - worst case – single crew

The one-to-one mapping between roads and jobs is presented in Figure 53. The Scheduling model's result can be seen in Figure 54.

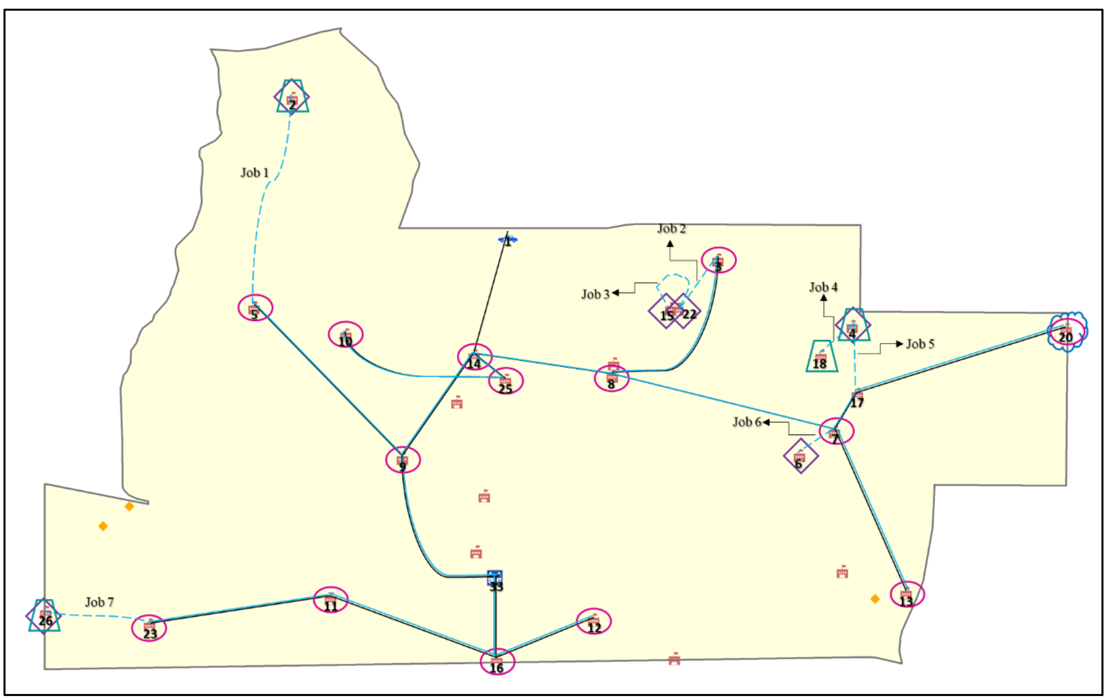


Figure 53. Jobs to schedule for priority 2 - worst case – single crew

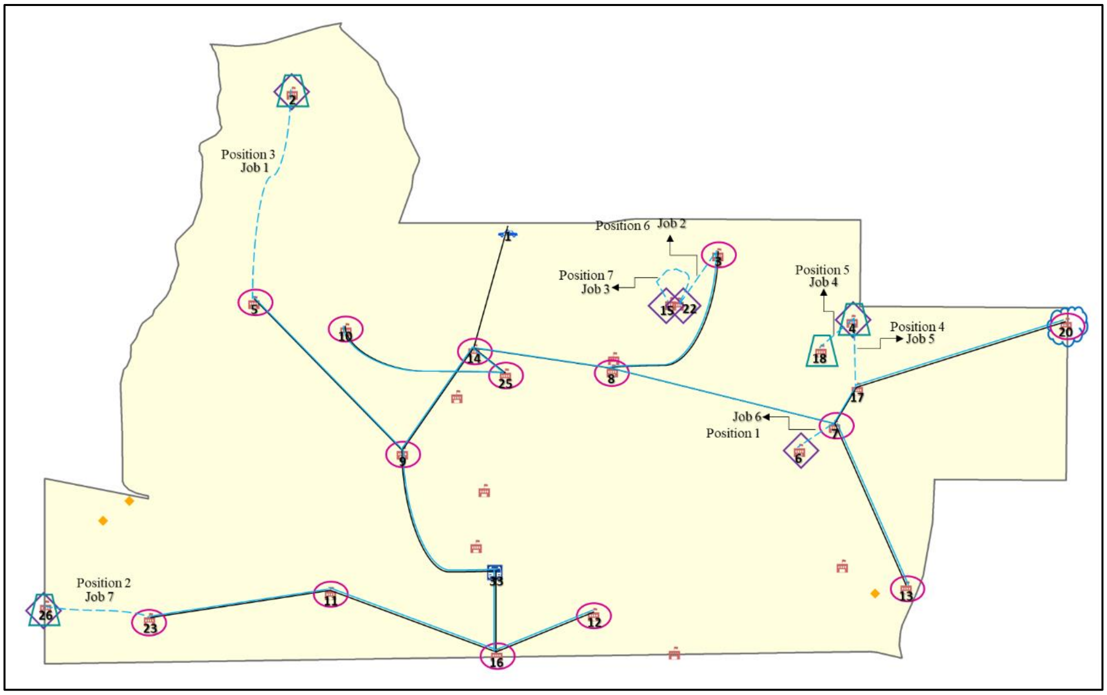


Figure 54. Crew's schedule for priority 2 - worst case – single crew

The restored infrastructure system that provides connection to all the essential facilities and shelters for the priority 2 group is presented in Figure 55.

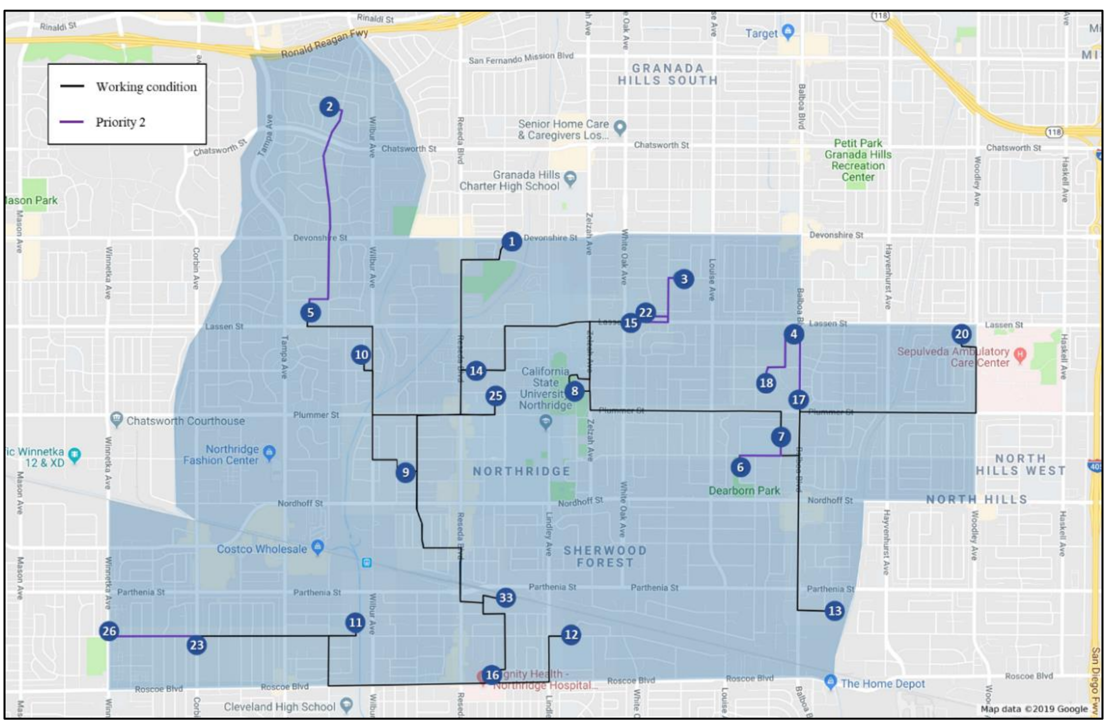


Figure 55. Restored road infrastructure system priority 2 - worst case – single crew

The updated infrastructure system which is the starting point for priority 3 group can be observed in Figure 56. It is important to highlight that in this priority group the objective is to connect the police station with the hazmat facilities. In this priority, the shelters are not considered because we do not want to connect shelters with hazmat facilities.

Figure 57 shows that as a part of the Steiner tree's solution only 3 new roads need to be fixed. In addition, 12 working roads needed to be used to be able to connect the facilities of interest in this priority group. Knowing that all the interdependency groups were addressed in the priority 2 solution, we did not have to check that situation here.

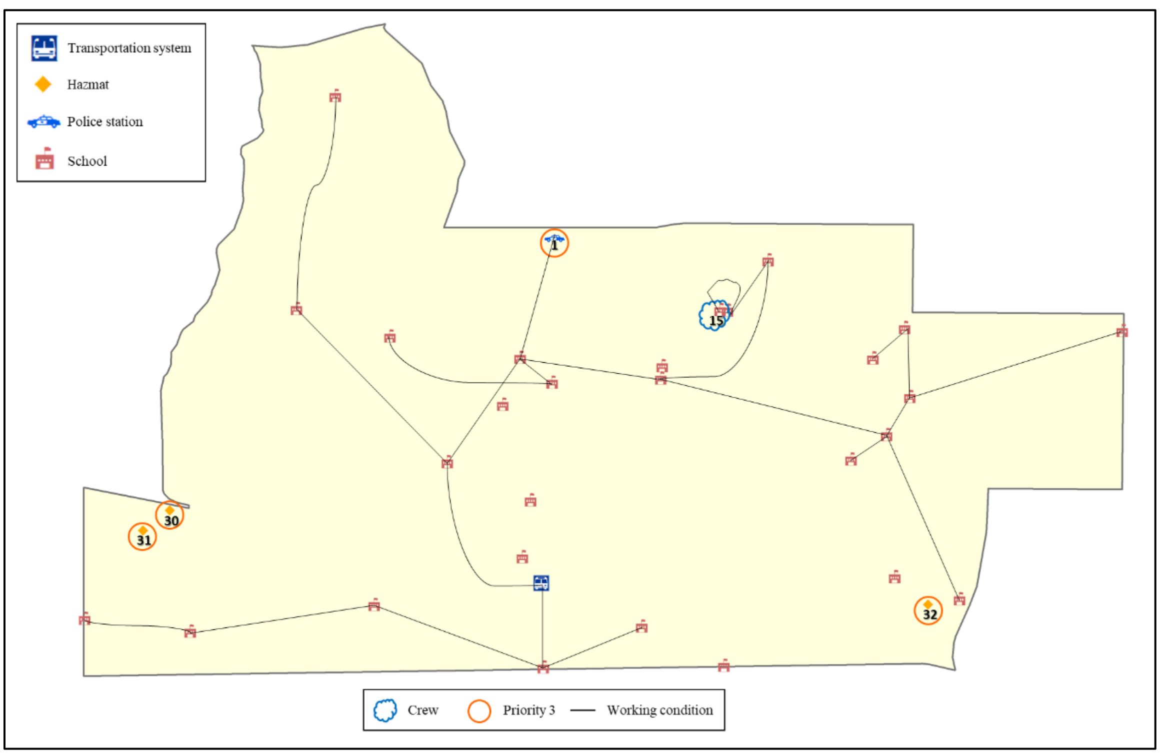


Figure 56. Initial road system for priority 3 - worst case – single crew

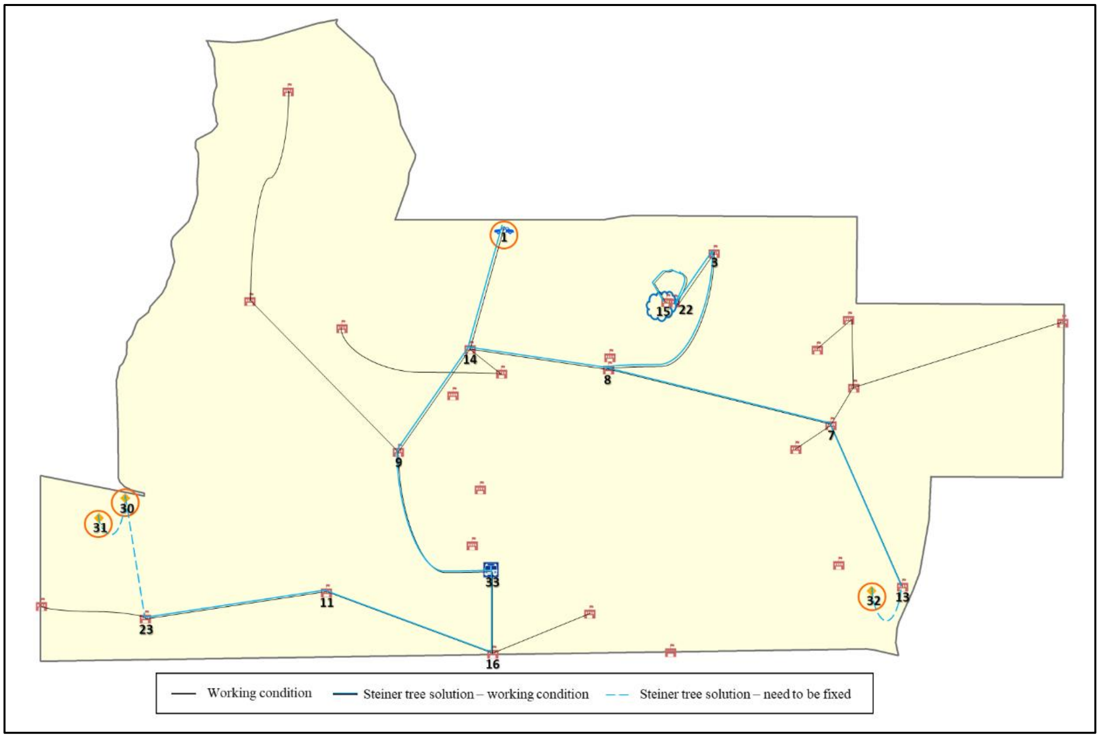


Figure 57. Steiner tree solution for priority 3 - worst case – single crew

The information required and the solution of the Scheduling model are presented in Figure 58 and Figure 59, respectively.

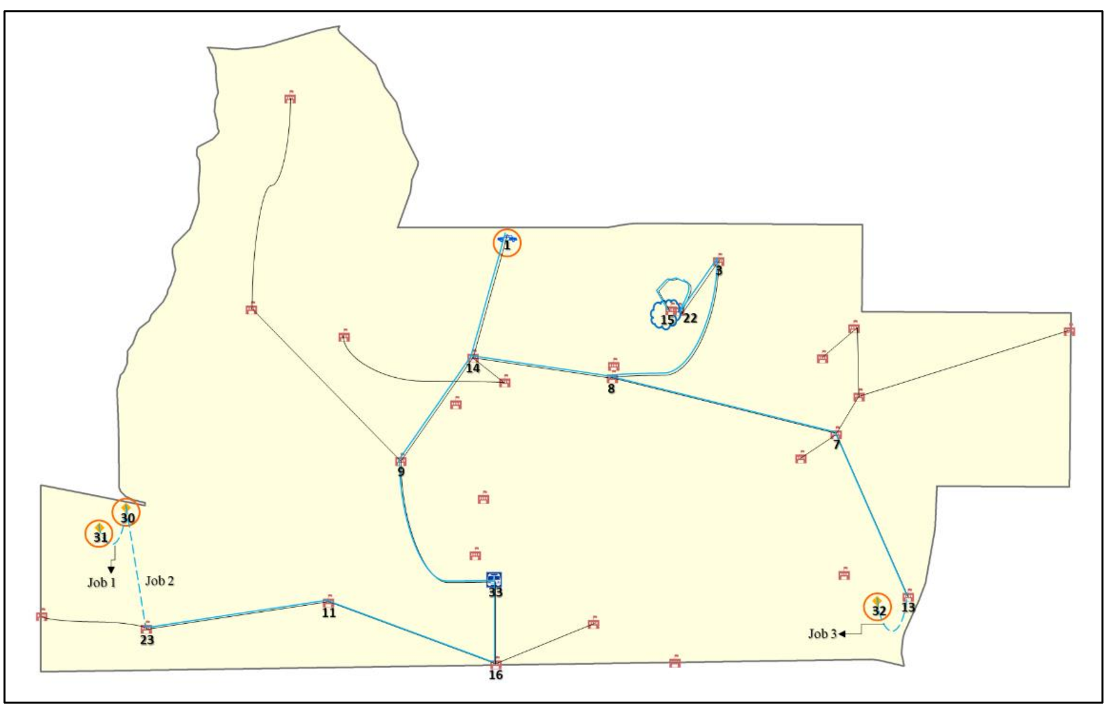


Figure 58. Jobs to schedule for priority 3 - worst case – single crew

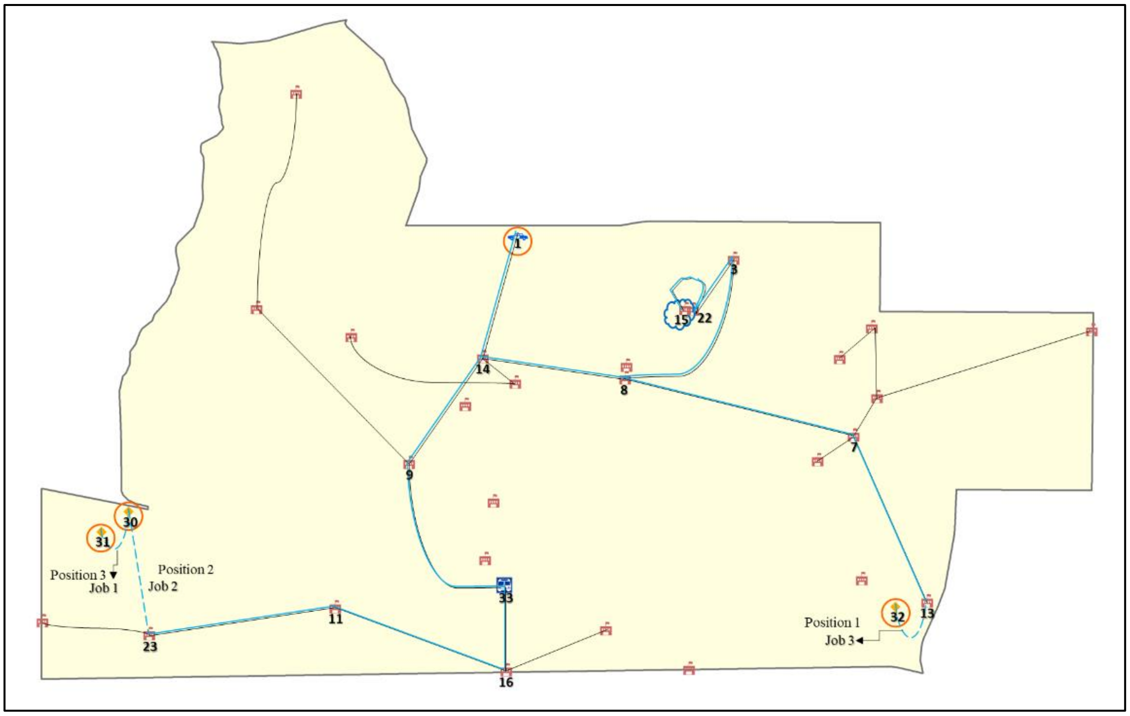


Figure 59. Crew's schedule for priority 3 - worst case – single crew

The restored infrastructure system for priority 3 group is presented in Figure 60.

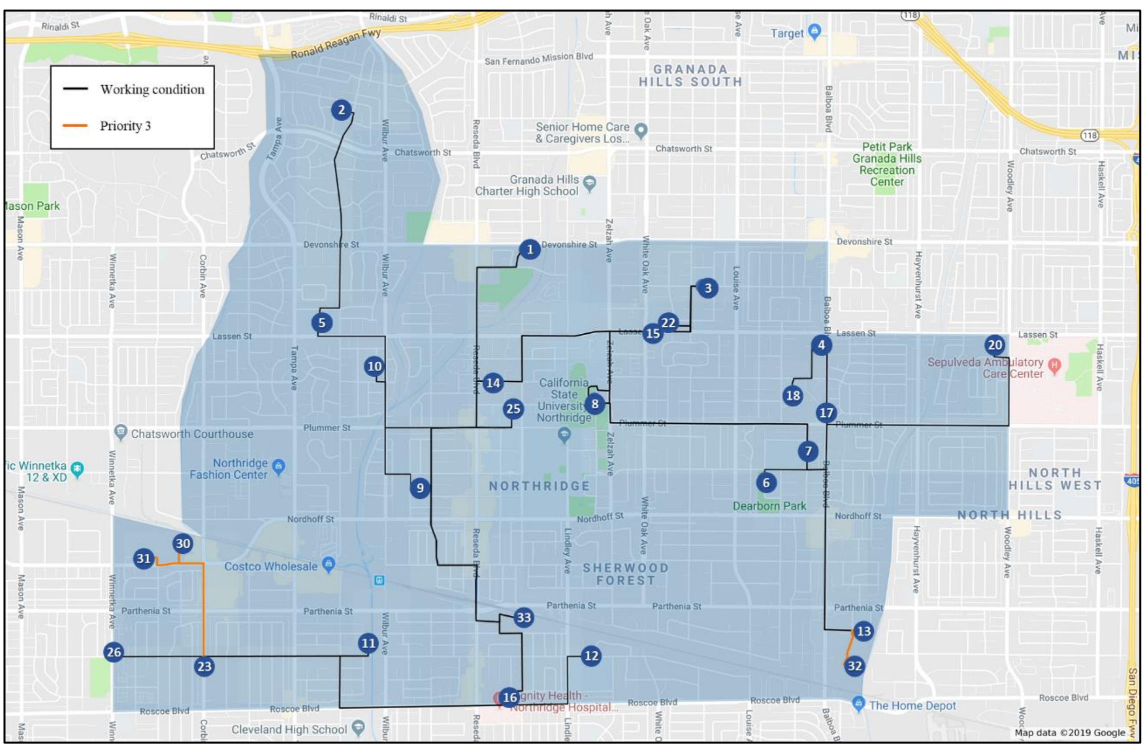


Figure 60. Restored road infrastructure system priority 3 - worst case – single crew

The infrastructure system that was considered as the starting point for non-priority facilities is presented in Figure 61. As it can be seen, there were 6 facilities that were not connected to the shelters. Due to this, we needed to once again apply our methodology.

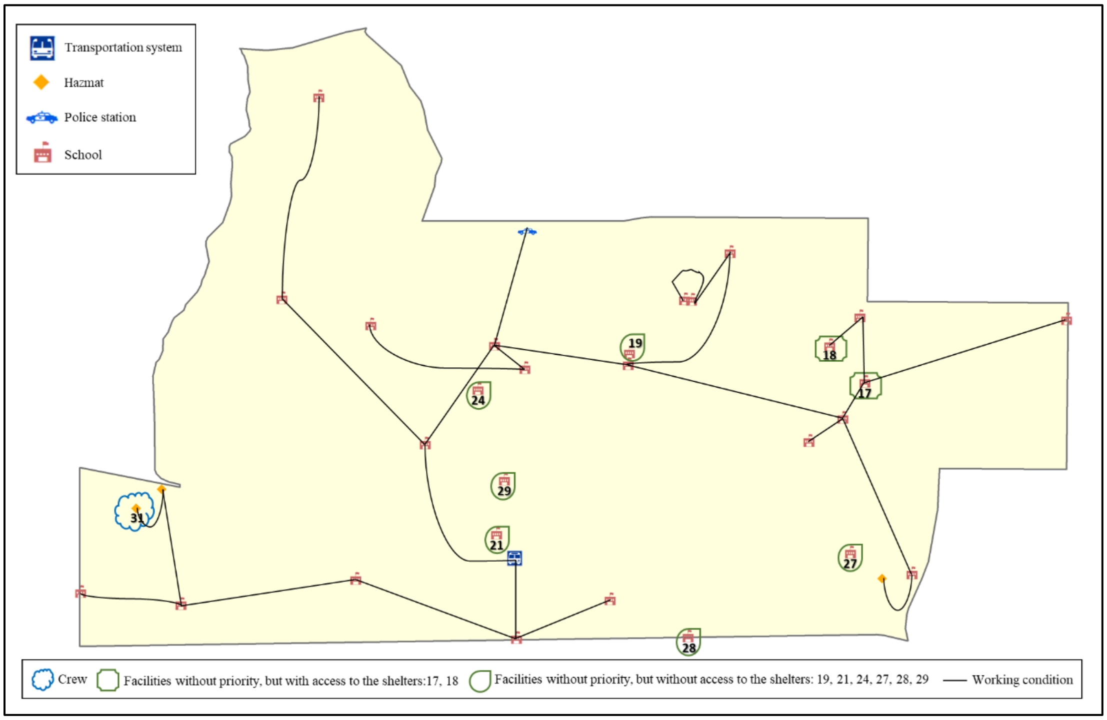


Figure 61. Initial road system for facilities with non-priority - worst case – single crew

The Steiner tree shows that 6 roads need to be fixed (Figure 62). The one-to-one mapping for the scheduling model and the crew schedule can be seen in Figure 63 and Figure 64.

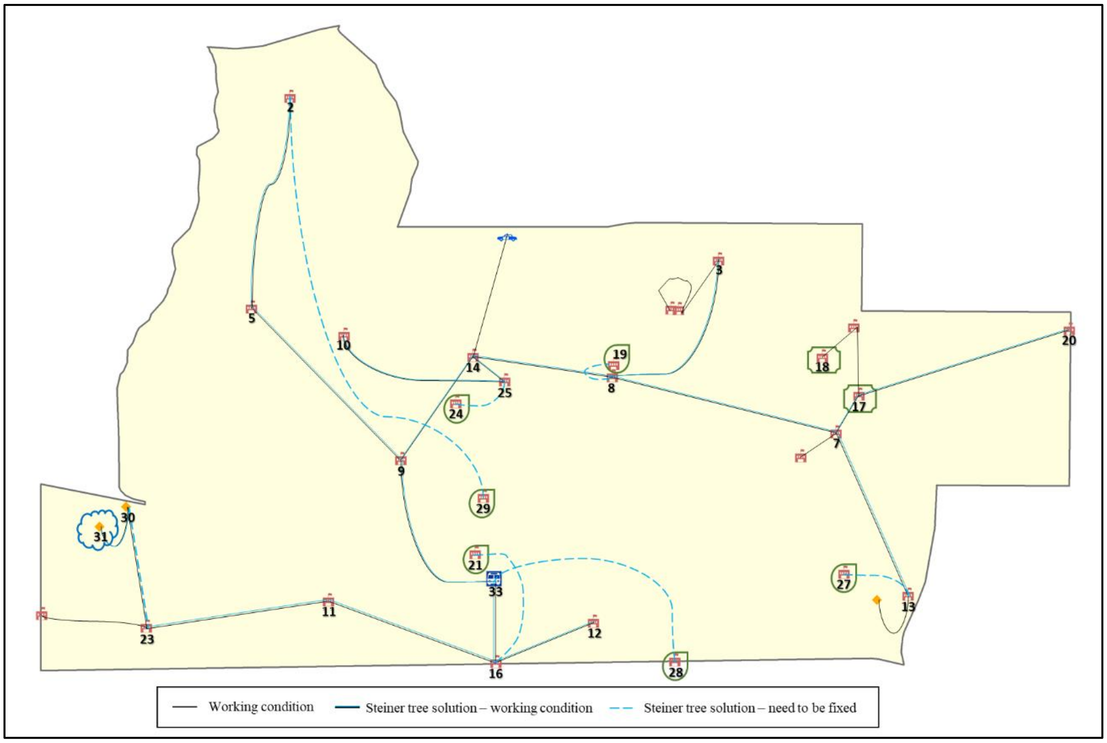


Figure 62. Steiner tree solution for facilities with non-priority - worst case – single crew

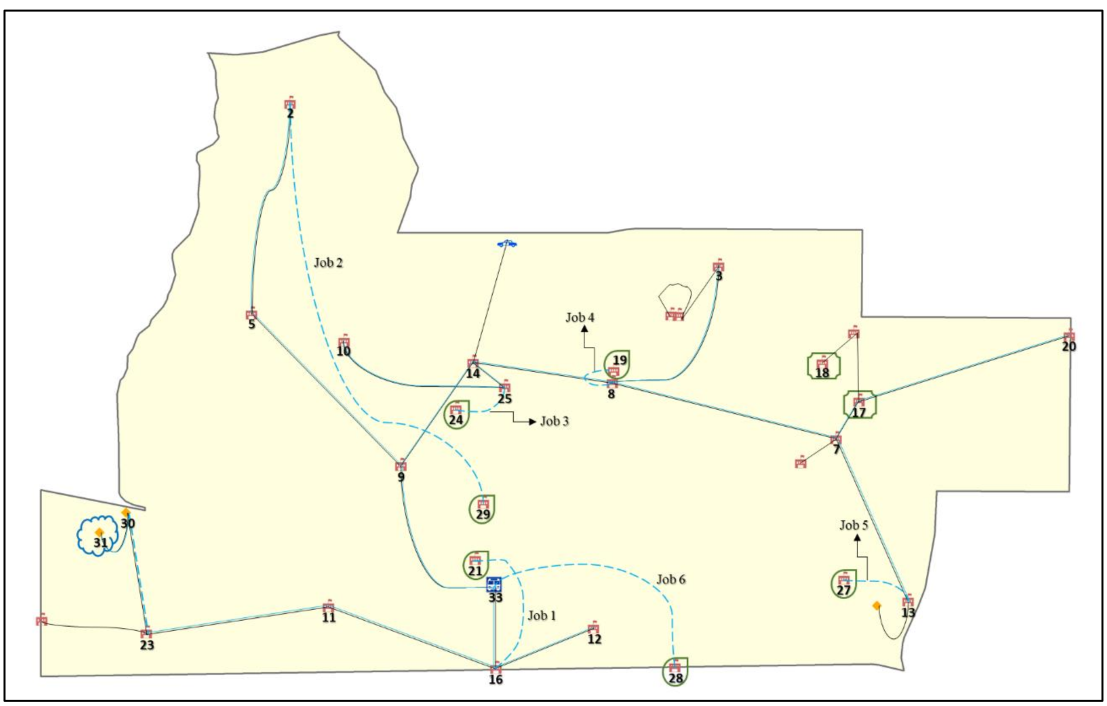


Figure 63. Jobs to schedule for facilities with non-priority - worst case – single crew

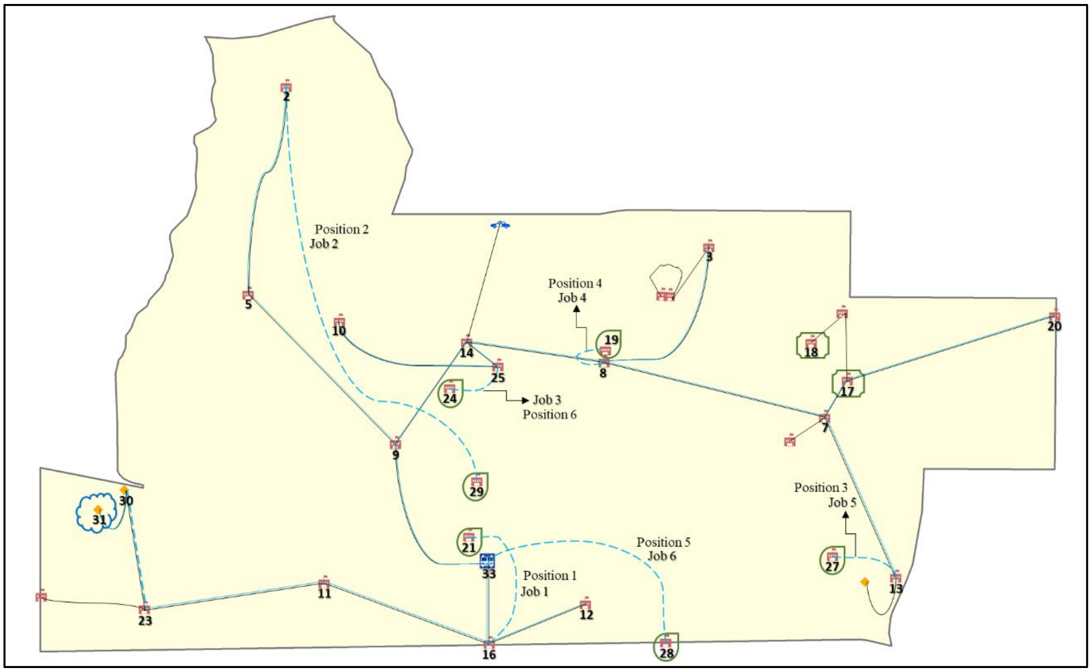


Figure 64. Crew's schedule for facilities with non-priority - worst case – single crew

After solving the non-priority facilities group, we have connection between all facilities. Figure 65 presents the final restored road infrastructure system. 32 of 528 roads were restored as a result of our methodology. In other words, only 6% of the infrastructure system needed to be restored in order to connect all the essential facilities in Northridge, CA.

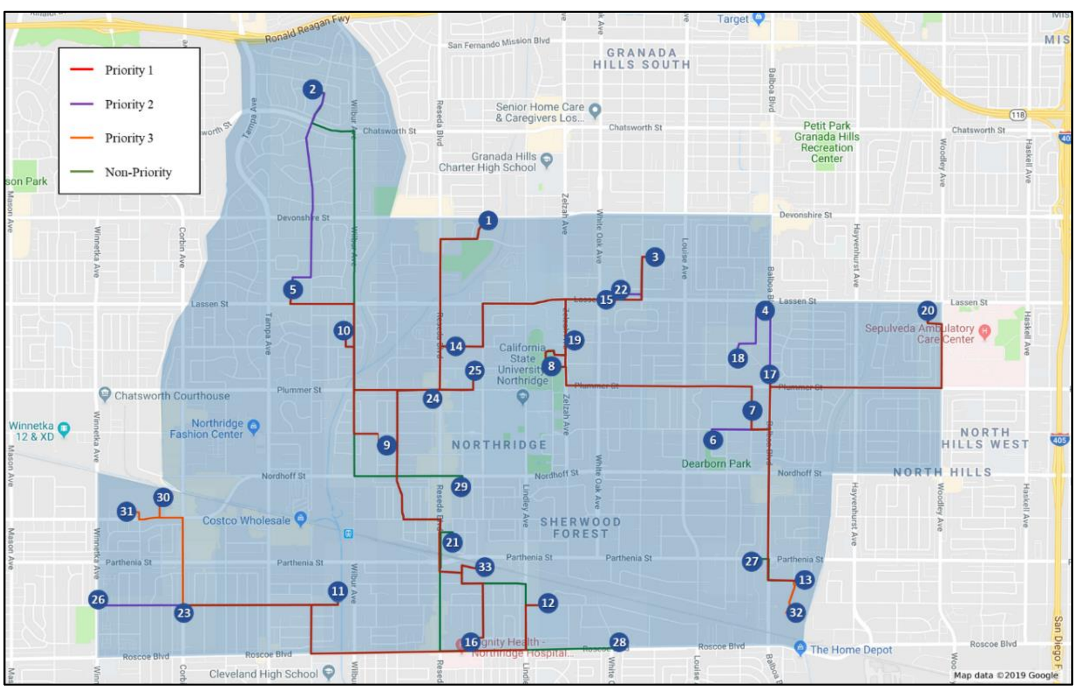


Figure 65. Final restored road infrastructure system - worst case – single crew

A summary of the crew's schedule by priority group is presented in Figure 66.

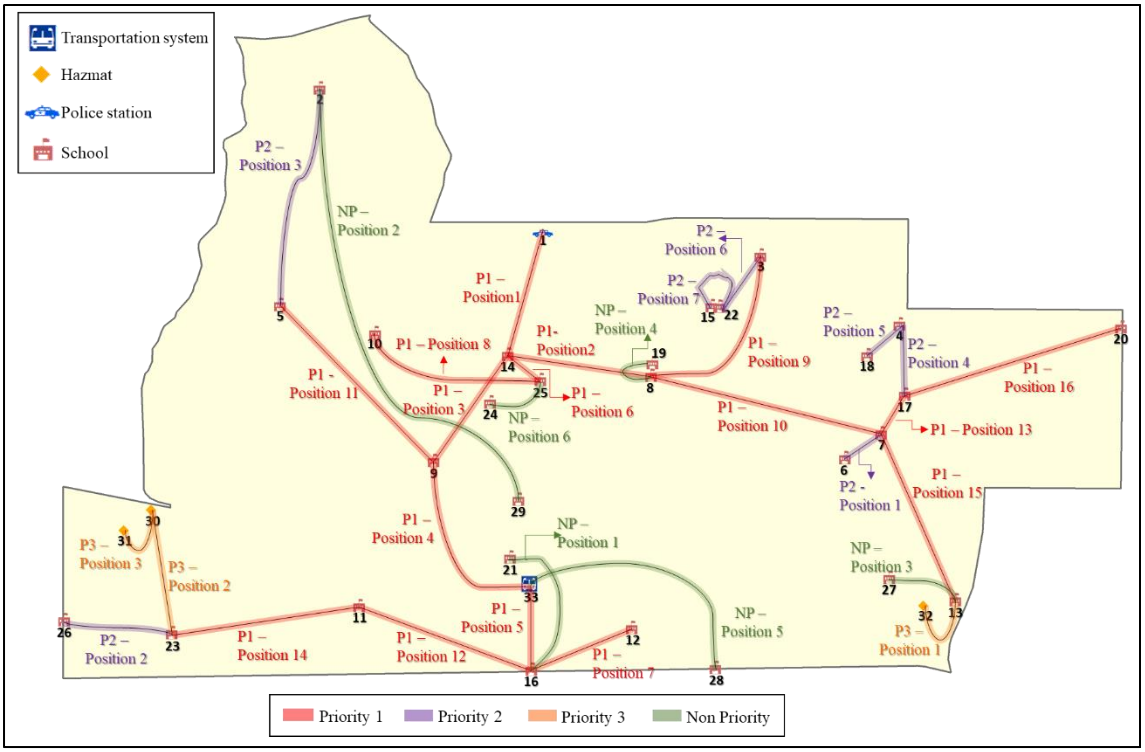


Figure 66. Final crew's schedule by priority groups - worst case – single crew

6.3.2 Northridge CA Worst Case – Multiple Crews

With the objective of presenting the application of our methodology when there is more than one crew available, we decided to solve the worst case scenario with two crews. Figure 67 shows the illustration of the road infrastructure system that we want to address. The only difference regarding the system presented in Figure 44. Illustration of road infrastructure system after an earthquake strikes – worst case – single crew is that there is a second crew located in facility 13.

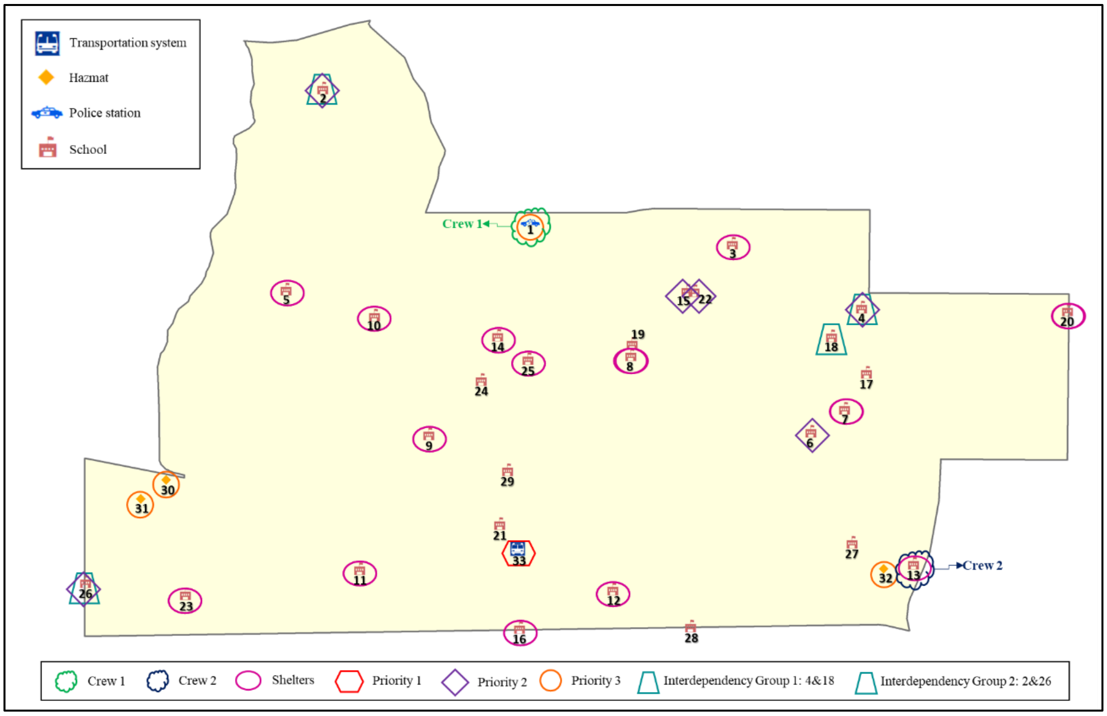


Figure 67. Illustration of road infrastructure system after an earthquake strikes – worst case – multiple crews

The priority 1 group essential facilities, shelters, and crews that need to be connected are presented in Figure 68.

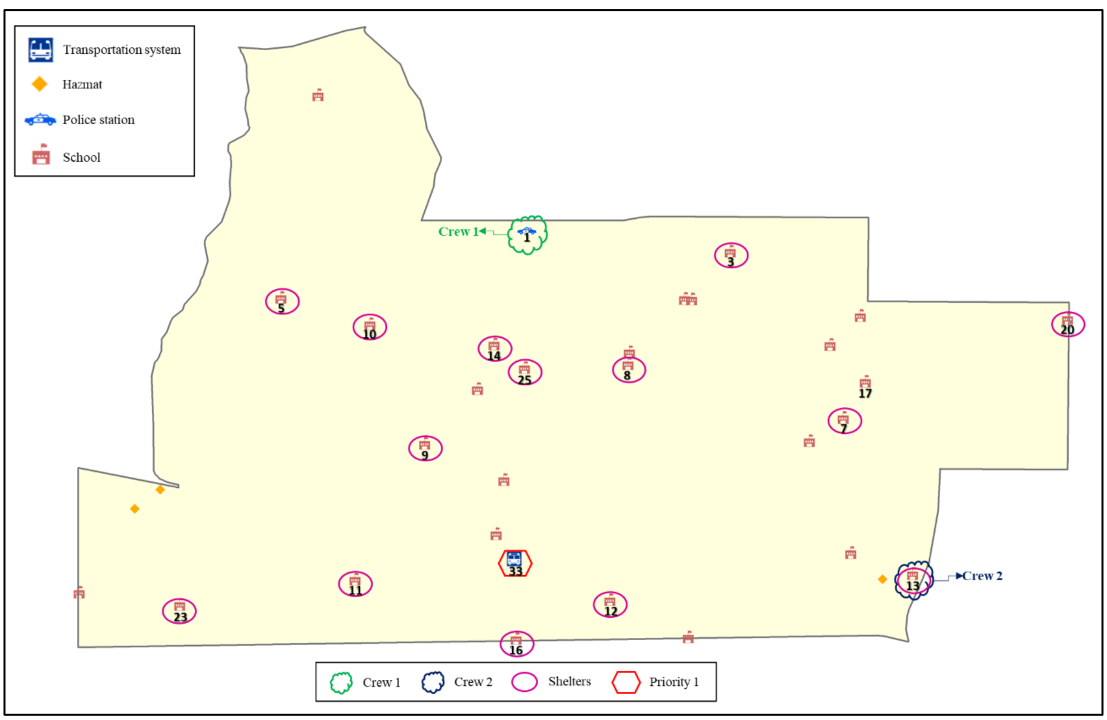


Figure 68. Initial road system for priority 1 - worst case – multiple crews

Figure 69 represented the Steiner tree solution for priority 1 group. This solution is exactly the same as the solution presented in Figure 47. Jobs to schedule for priority 1 - worst case – single crew. 16 roads need to be fixed to be able to connect all the points of interest.

Figure 70 showed the one-to-one mapping between roads and jobs. The crews' schedule is presented in Figure 71.

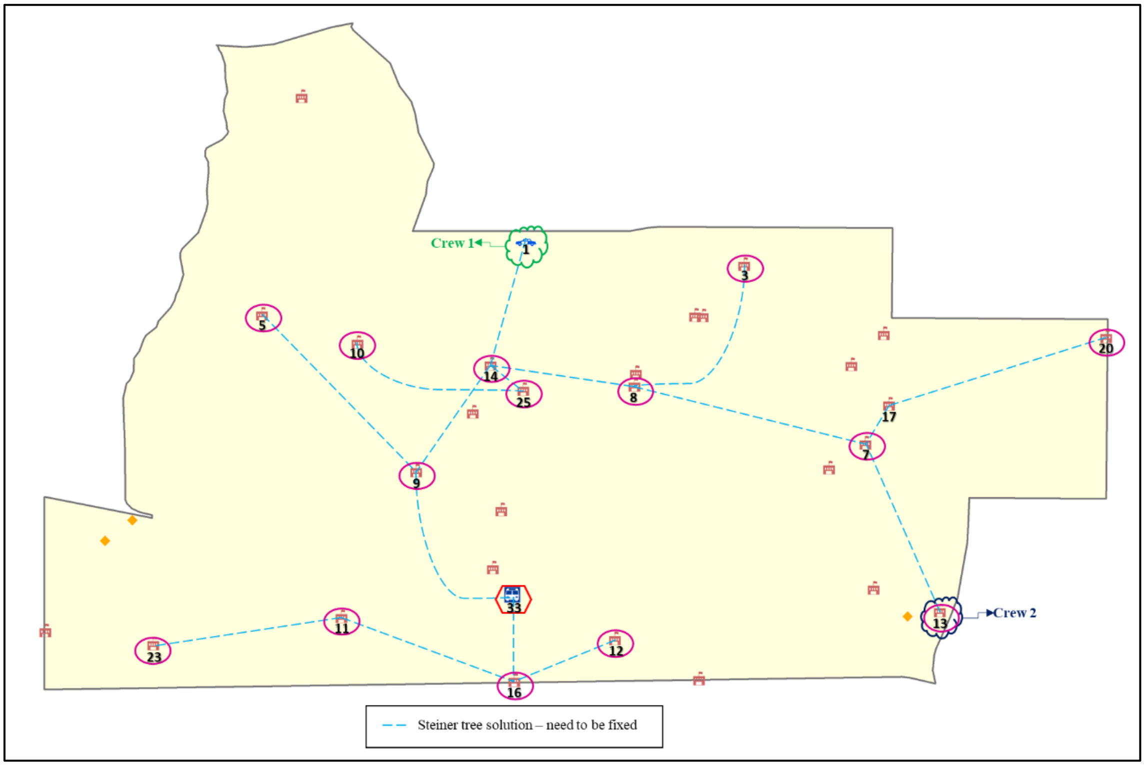


Figure 69. Steiner tree solution for priority 1 - worst case – multiple crews

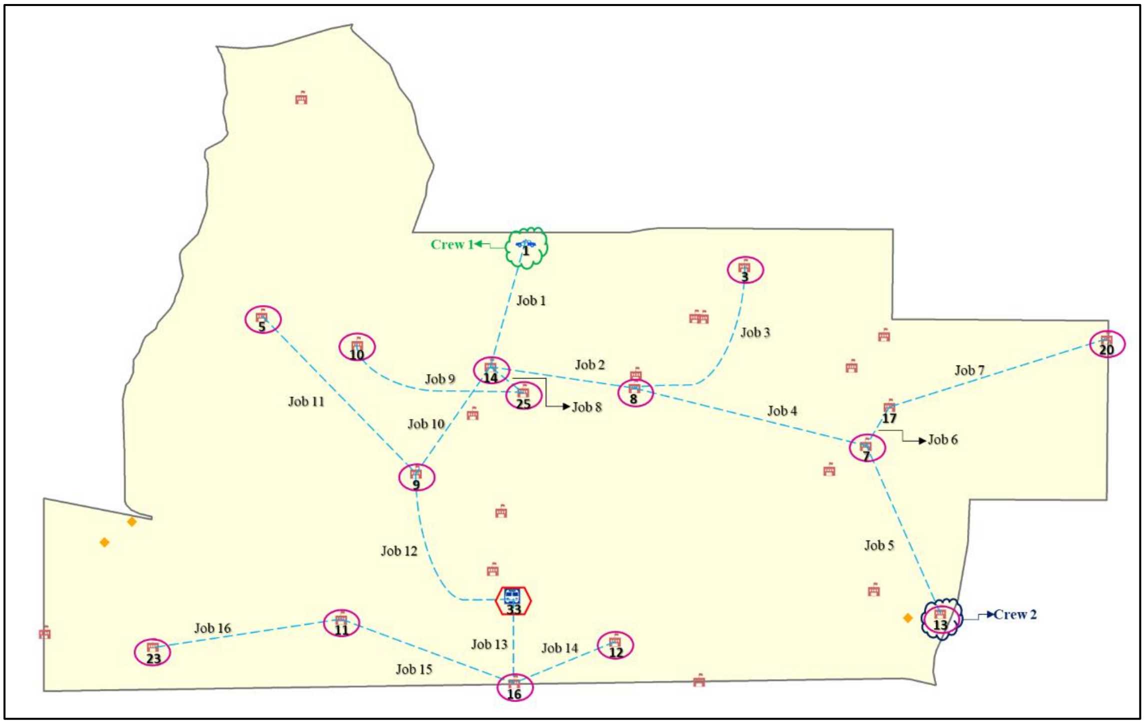


Figure 70. Jobs to schedule for priority 1 - worst case – multiple crews

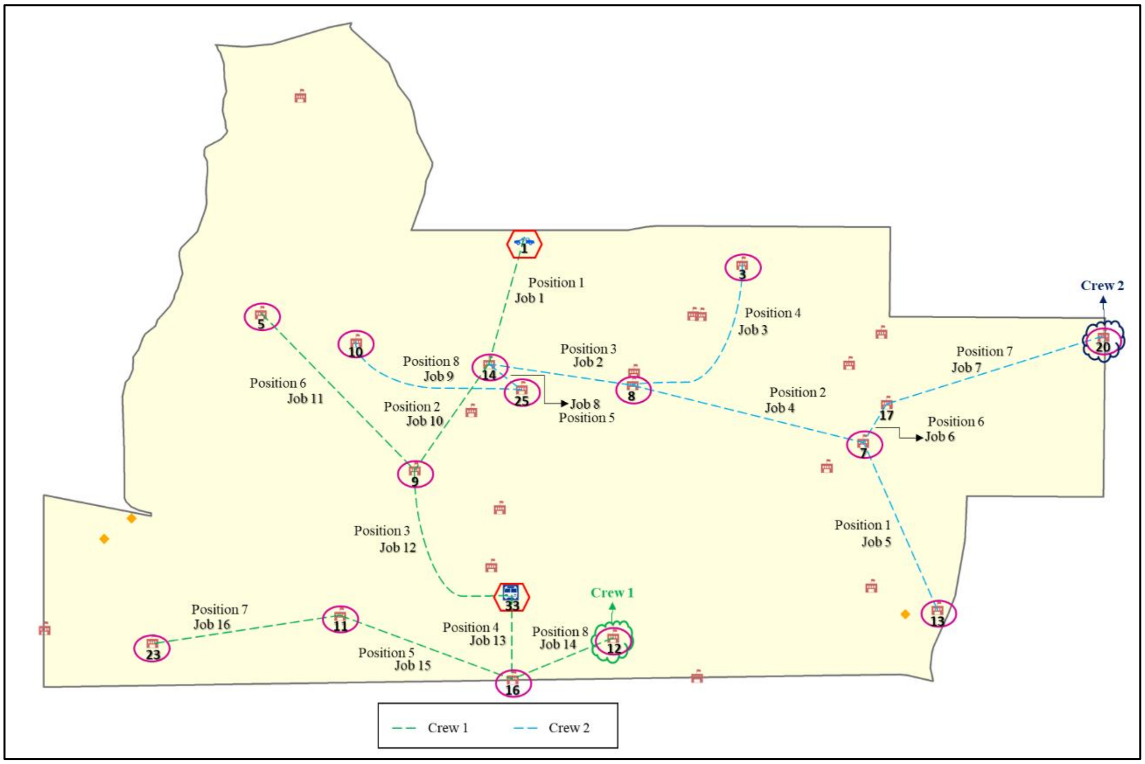


Figure 71. Crews' schedule for priority 1 - worst case – multiple crews

As it can be seen in Figure 71, both crews will be working on the reconstruction of 8 roads. The restored road infrastructure system priority 1 group was the starting point for the priority 2 group (see Figure 72).

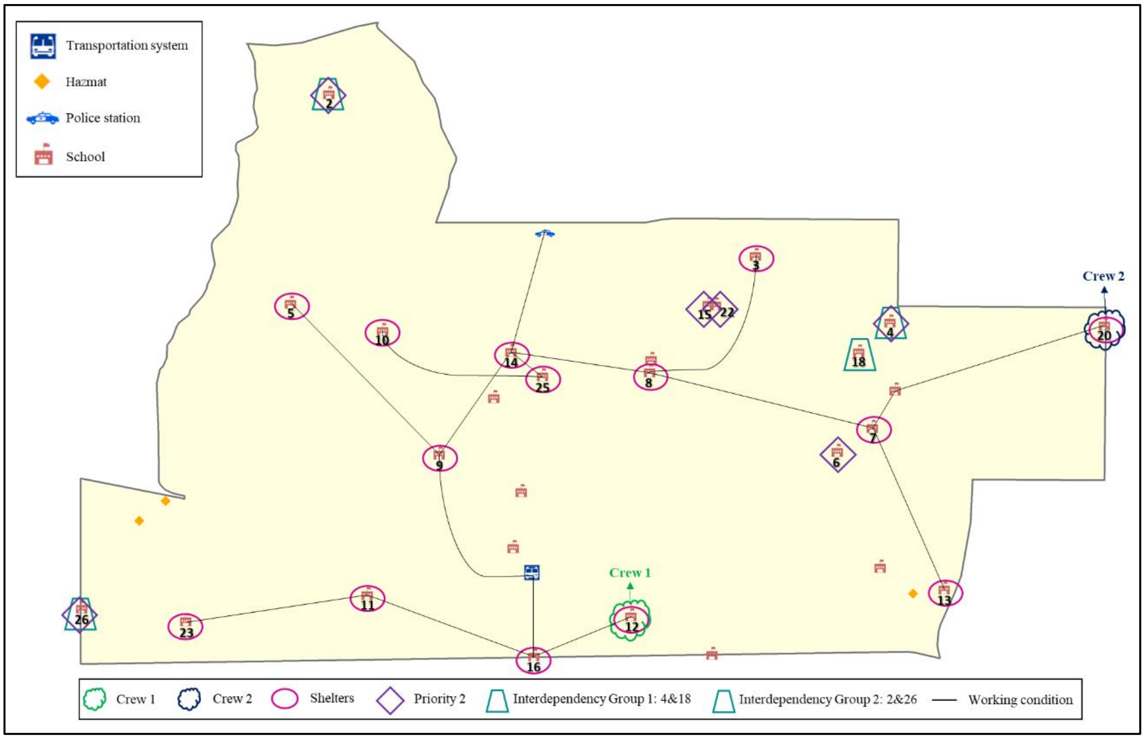


Figure 72. Initial road system for priority 2 - worst case – multiple crews

As it was expected the Steiner tree solution for priority 2 (see Figure 73) was the same as the one presented in Figure 51. Steiner tree solution for priority 2 - worst case – single crew. Due to this, both interdependency groups were included in the priority 2 solution. After re-running the Steiner tree model including facility 18 as part of priority 2 group, we obtained the solution presented in Figure 74.

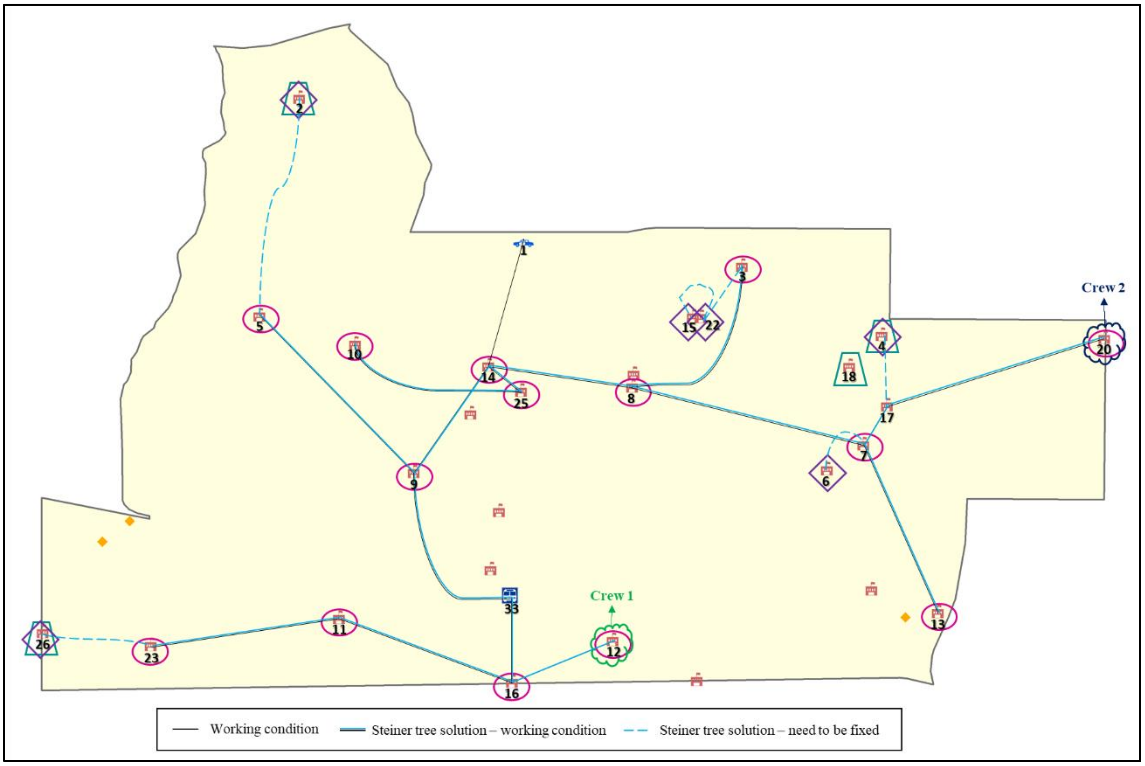


Figure 73. Steiner tree solution for priority 2 - worst case – multiple crews

The solution for this scenario is a little bit different than the solution presented in Figure 52. Steiner tree solution for priority 2 with interdependencies - worst case – single crew. The difference is that, for the worst case multiple crews' scenario, the job identified as number 5 is the road between facilities 17 and 18 while it is the road between facilities 4 and 17 for the worst case single crew's scenario. The cause of this difference is that the Steiner tree model for priority 1 with interdependencies scenario has multiple solutions. This means that these two solutions are equivalent because in both cases job 5 has a reconstruction time of 19.6 days.

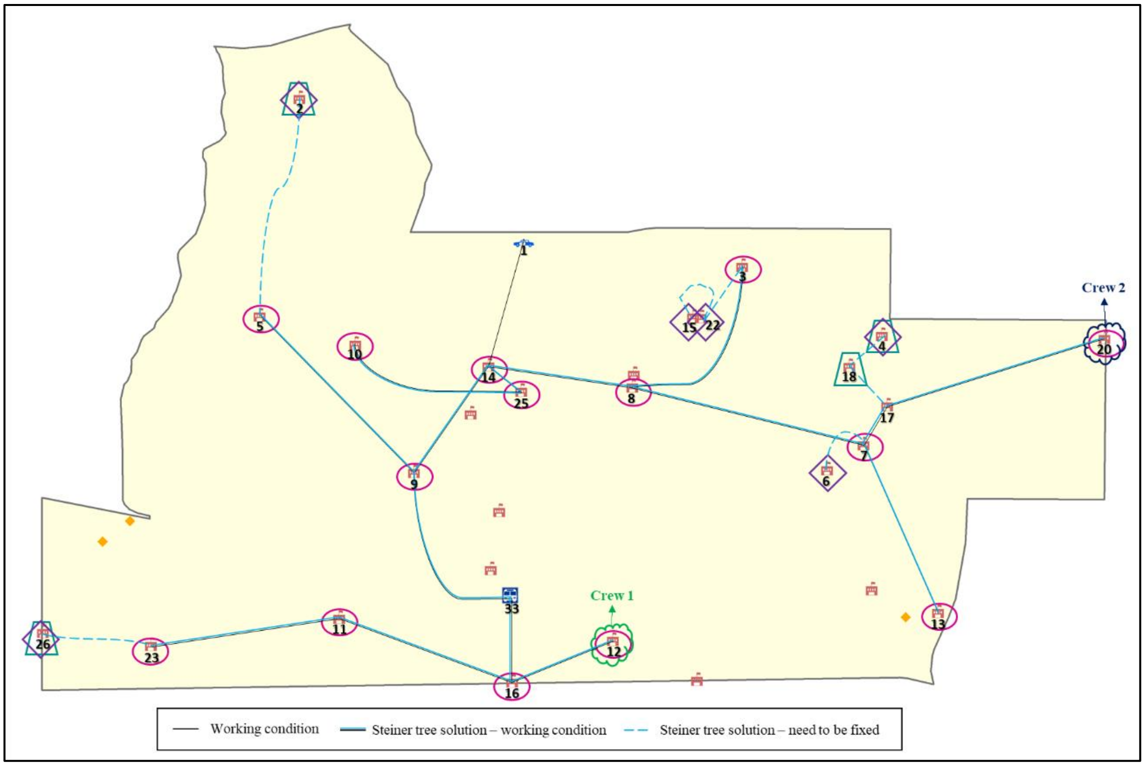


Figure 74. Steiner tree solution for priority 2 with interdependencies - worst case – multiple crews

The one-to-one mapping between roads and jobs is presented in Figure 75. The Scheduling model's result can be seen in Figure 76. Crew 1 will be responsible for rebuilding 5 roads for which reconstruction time is 68.6 days. In contrast, crew 2 would work on one road with reconstruction time of 196 days.

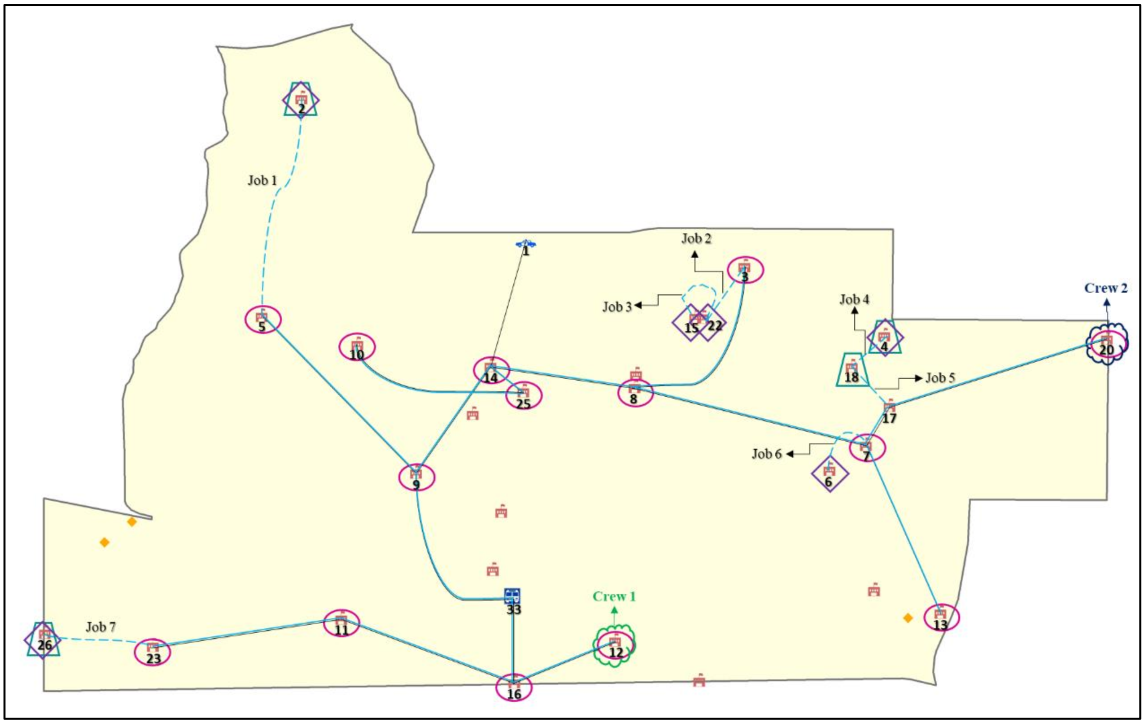


Figure 75. Jobs to schedule for priority 2 - worst case – multiple crews

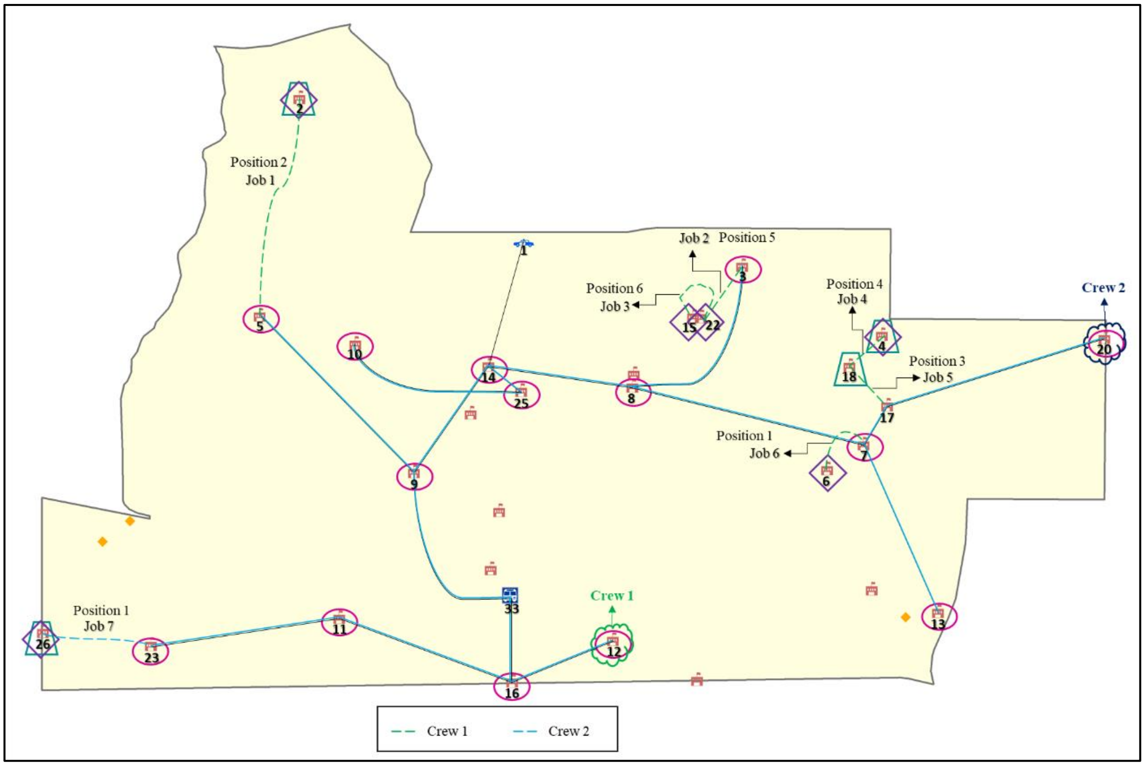


Figure 76. Crews' schedule for priority 2 - worst case – multiple crews

The restored infrastructure system that provides connection between all the essential facilities and shelters for the priority 2 group is presented in Figure 77. This figure also represents the starting point for priority 3 group. As it was mentioned before, in priority 3 group our objective is to connect the police station with the hazmat facilities.

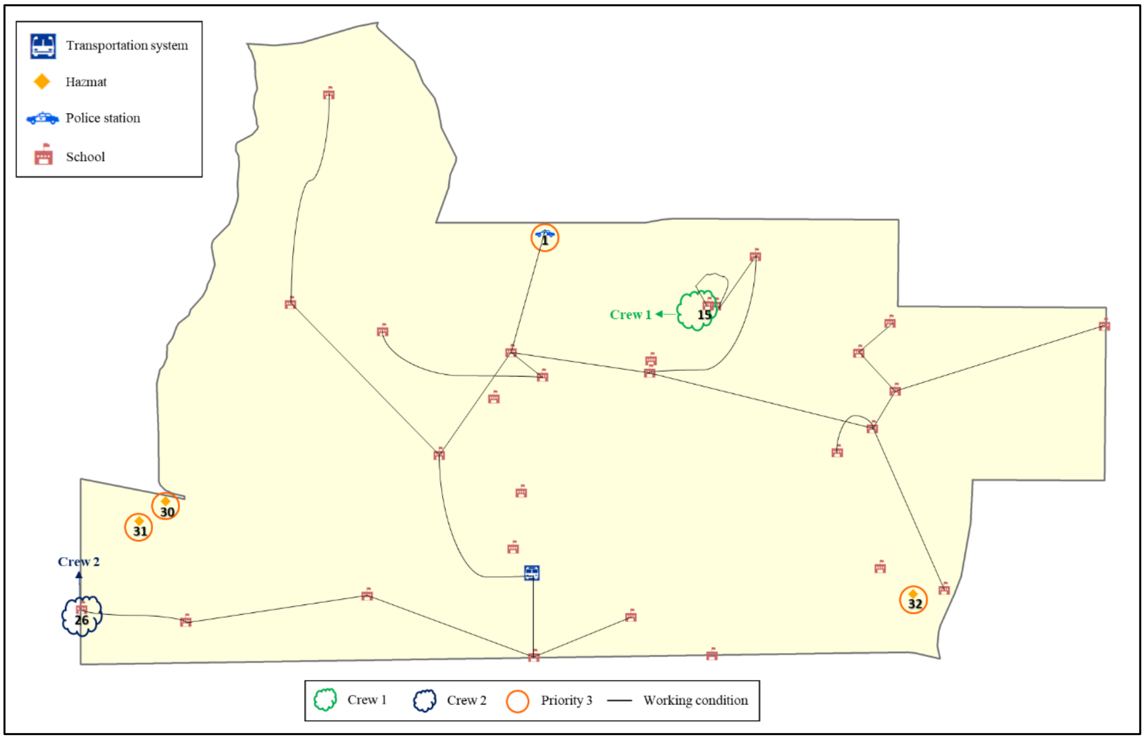


Figure 77. Initial road system for priority 3 - worst case – multiple crews

The Steiner tree's solution presented in Figure 78 is the same as the one presented in Figure 57. Steiner tree solution for priority 3 - worst case – single crew. The information required for the Scheduling model is presented in Figure 79.

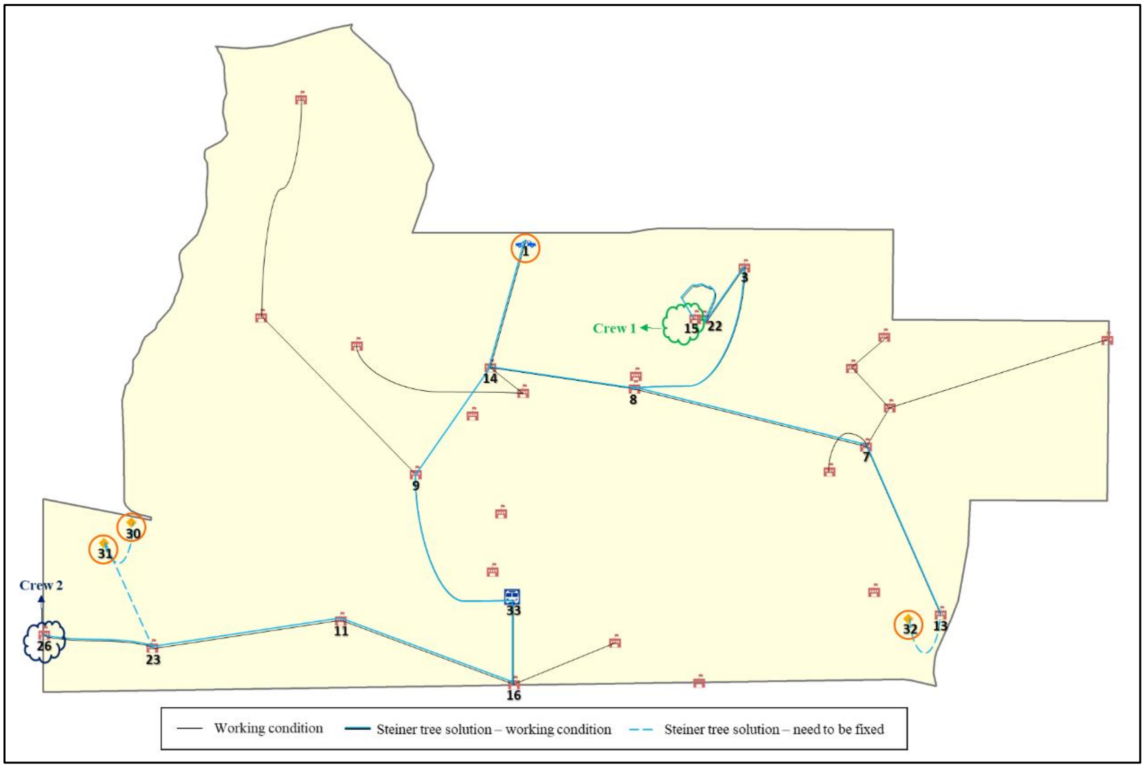


Figure 78. Steiner tree solution for priority 3 - worst case – multiple crews

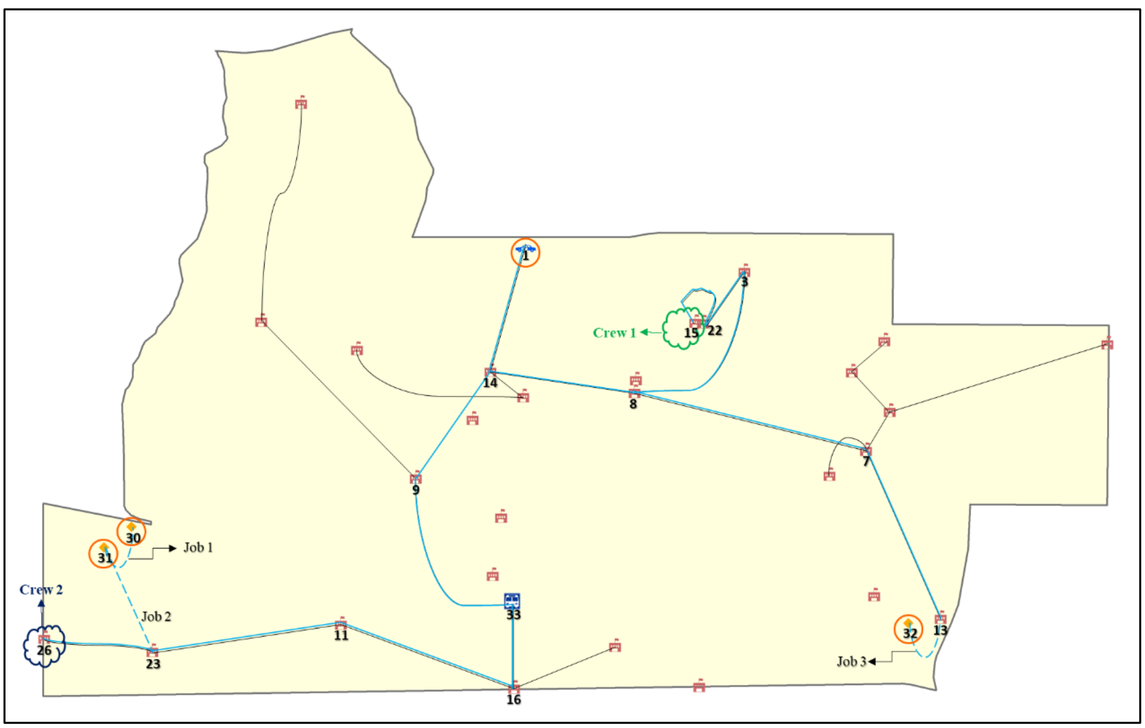


Figure 79. Jobs to schedule for priority 3 - worst case – multiple crews

The scheduling model's solution is presented in Figure 80. In this case, crew 1 will be responsible for 1 road while crew 2 will be responsible for 2 roads.

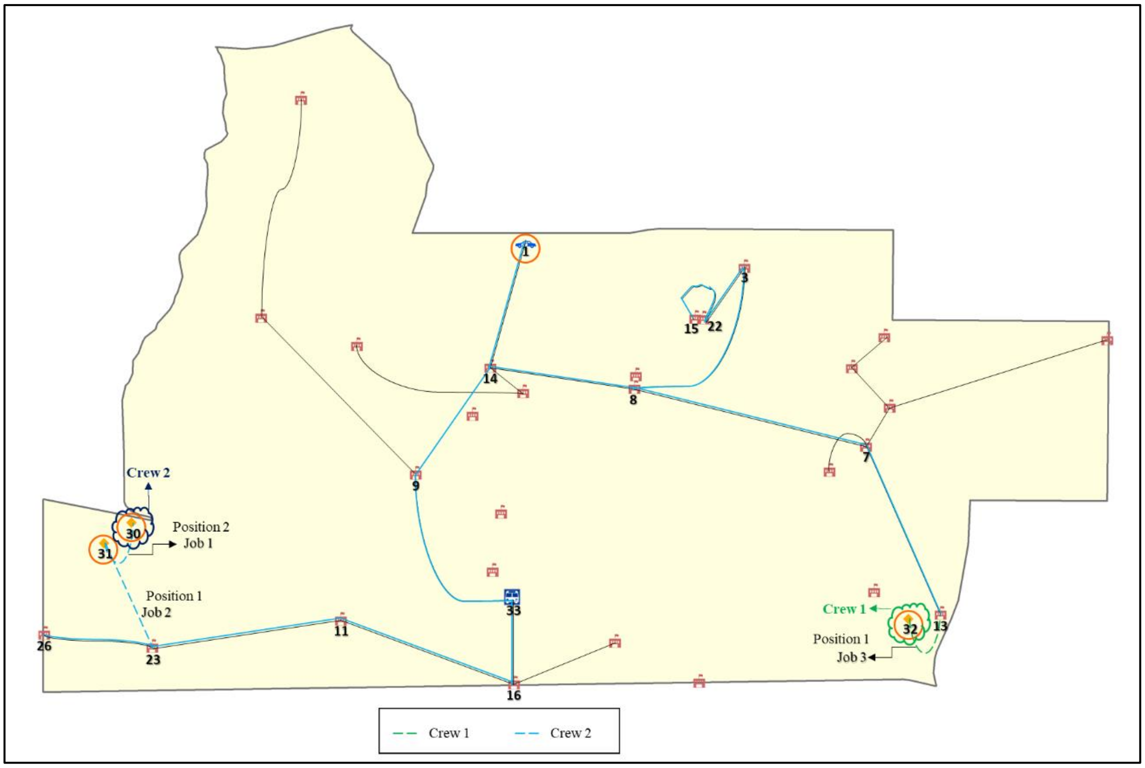


Figure 80. Crew's schedule for priority 3 - worst case – multiple crews

The restored road infrastructure system for priority 3 group which was considered the starting point for the non-priority facilities is presented in Figure 81. The Steiner tree solution showed that 6 roads need to be fixed (see Figure 82).

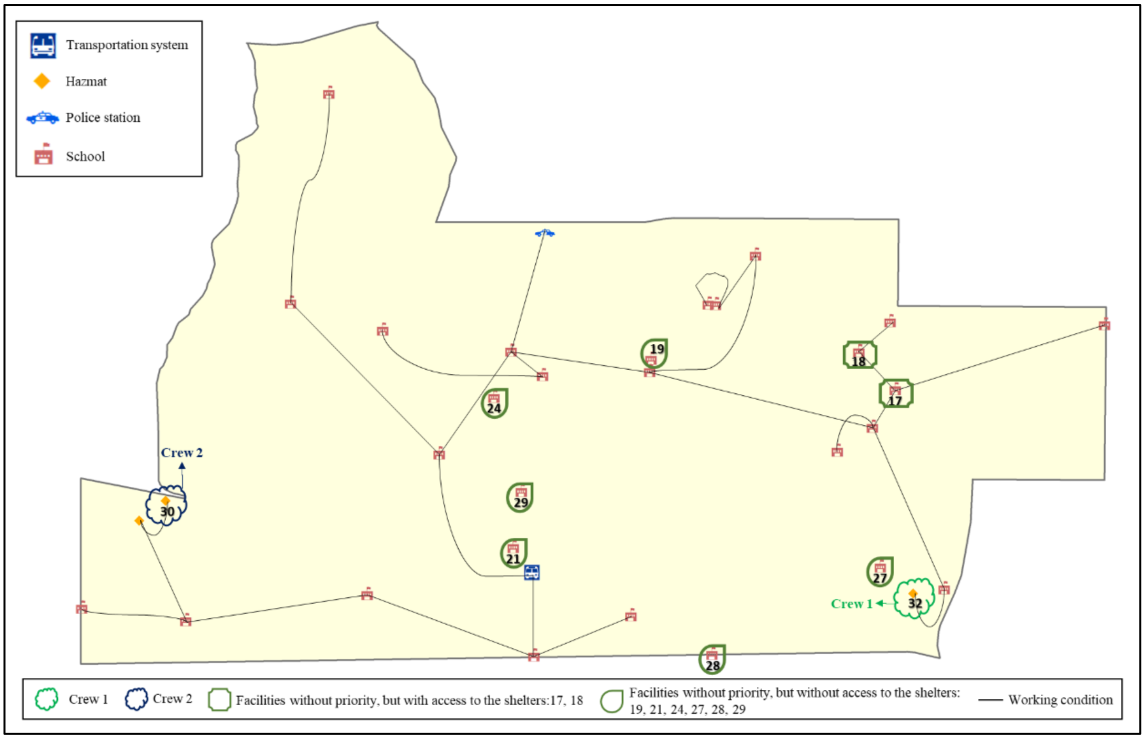


Figure 81. Initial road system for facilities with non-priority - worst case – multiple crews

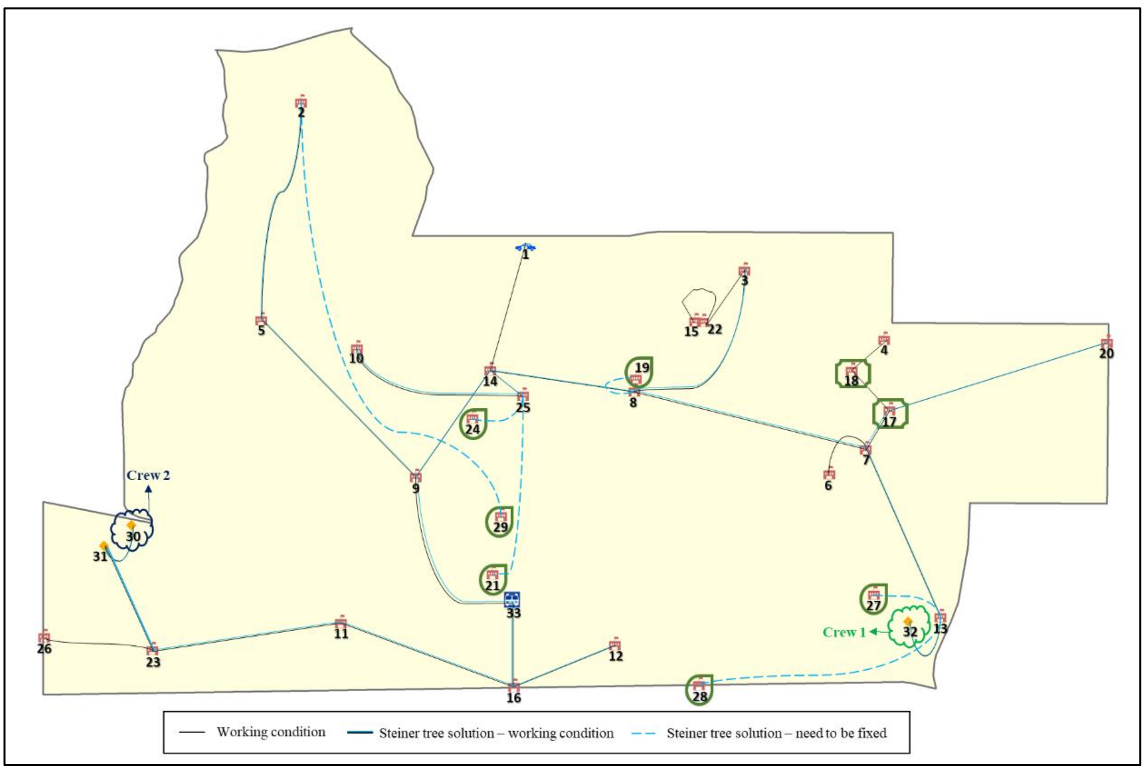


Figure 82. Steiner tree solution for facilities with non-priority - worst case – multiple crews

The one to one mapping for the Scheduling model and its solution is presented in Figure 83 and Figure 84, respectively.

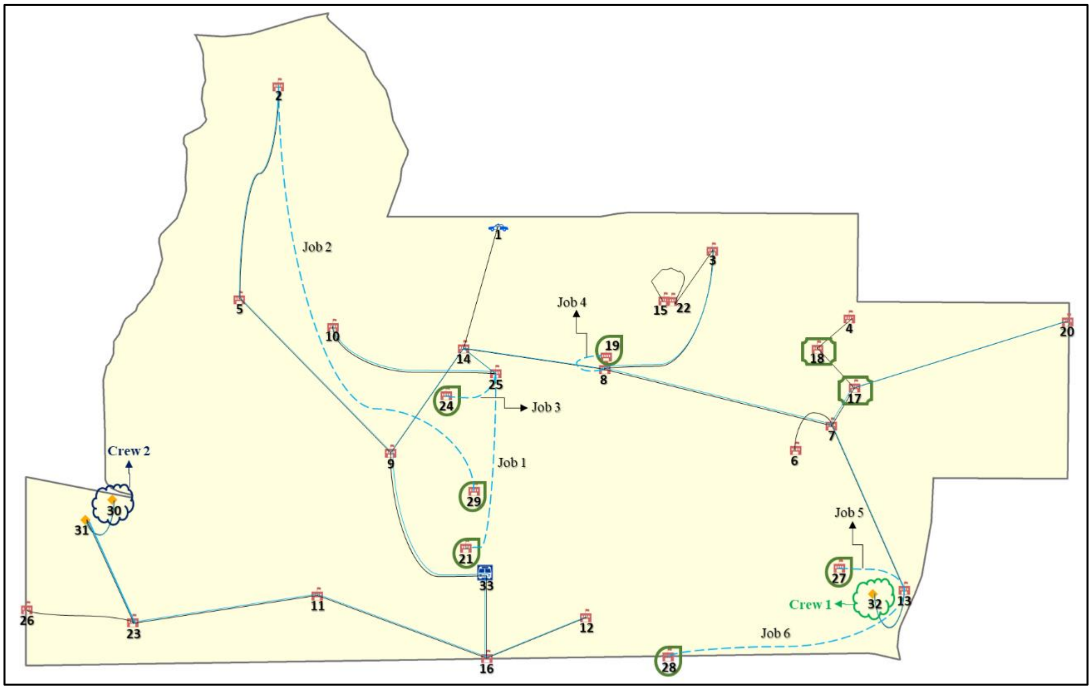


Figure 83. Jobs to schedule for facilities with non-priority - worst case – multiple crews

As it can be seen in Figure 84, both crews will be working in the reconstruction of 3 roads each.

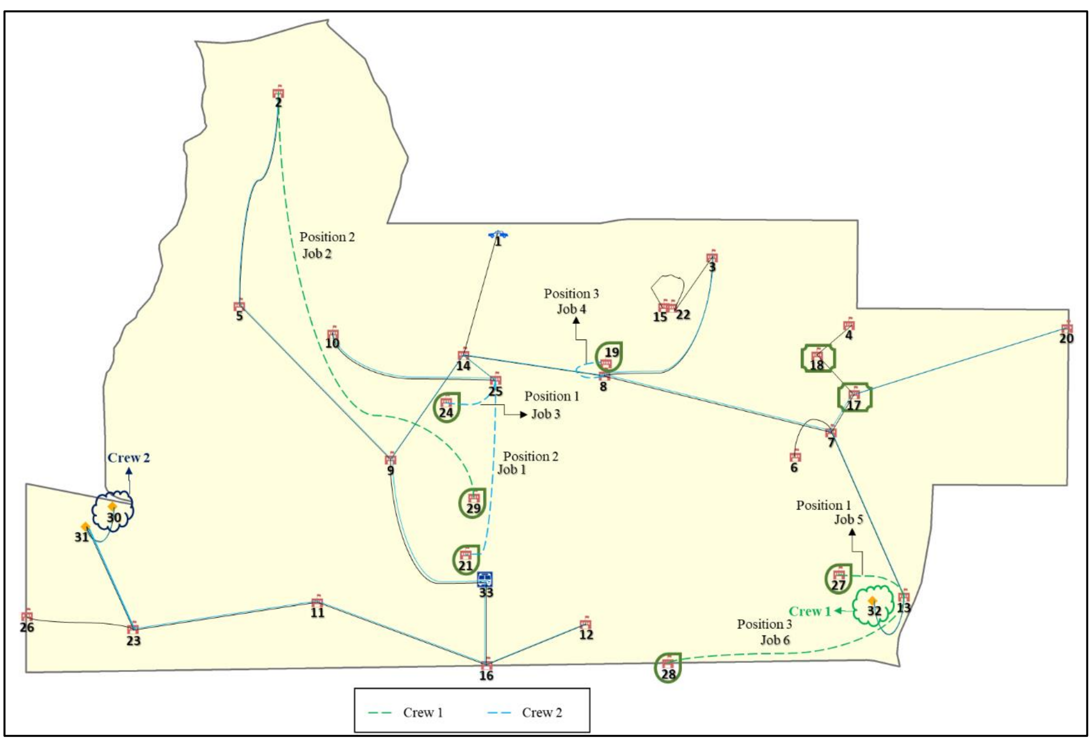


Figure 84. Crews' schedule for facilities with non-priority - worst case – multiple crews

The final restored road infrastructure system for the worst case scenario with multiple crews shows that 32 (6%) roads need to be fixed. The final representation of the restored system is presented in Figure 85.

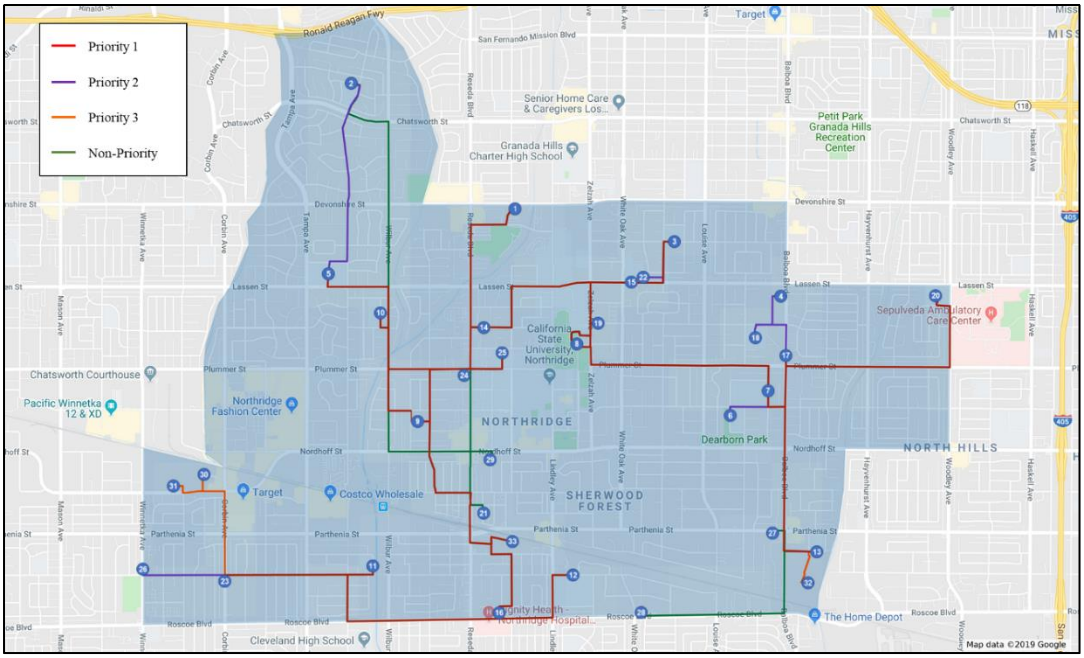


Figure 85. Final restored road infrastructure system - worst case – multiple crews

A summary of the crews' schedule can be observed in Figure 86 and Table 25.

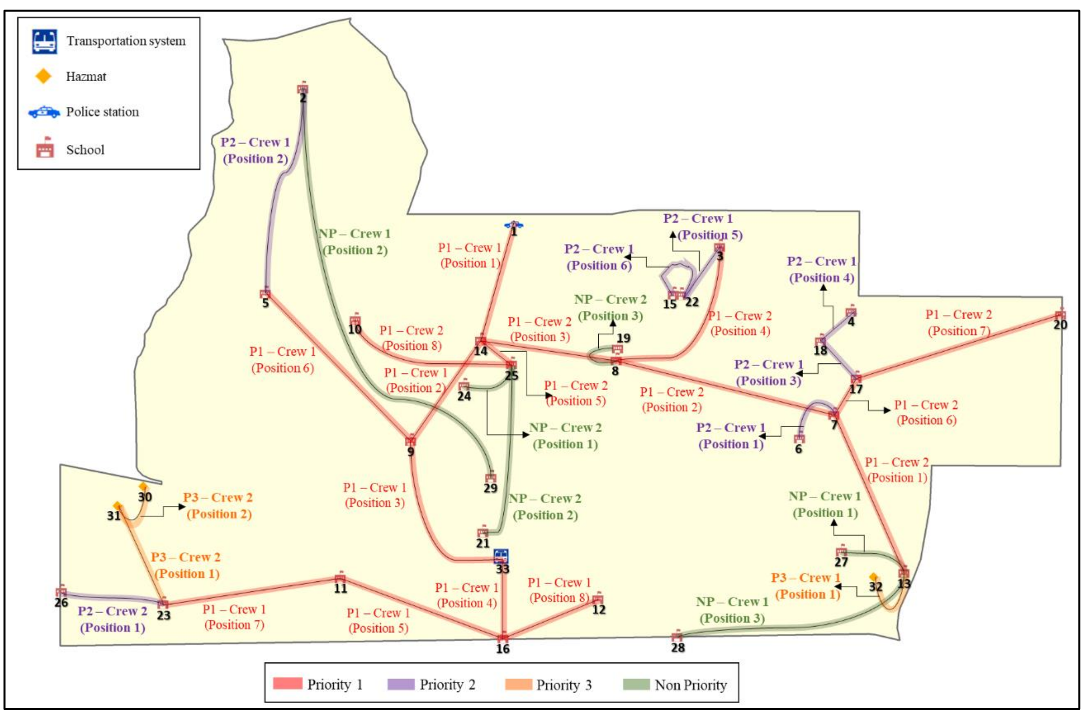


Figure 86. Final crews' schedule by priority groups- worst case – multiple crews

Table 25: Crews' schedule by priority groups

PRIORITIES	POSITION	CREW 1 From __ to __	CREW 2 From __ to __
1	1	Job 1: 1 - 14	Job 5: 13 – 7
	2	Job 10: 14 - 9	Job 4: 7 – 8
	3	Job 12: 9 - 33	Job 2: 8 – 14
	4	Job 13: 33 - 16	Job 3: 8 – 3
	5	Job 15: 16 - 11	Job 8: 14 – 25
	6	Job 11: 9 - 5	Job 6: 7 – 17
	7	Job 16: 11 - 23	Job 7: 17 – 20
	8	Job 14: 16 - 12	Job 9: 25 - 10
2	1	Job 6: 7 – 6	Job7: 23 - 26
	2	Job 1: 5 – 2	
	3	Job 5: 17 – 18	
	4	Job 4: 18 – 4	
	5	Job 2: 3 - 22	
	6	Job 3: 22 - 15	
3	1	Job 3: 13 - 32	Job 2: 23 – 31
	2		Job 1: 31 – 30
Non priority	1	Job 5: 13 - 27	Job 3: 25 - 24
	2	Job 2: 2 – 29	Job 1: 25 – 21
	3	Job 6: 13 - 28	Job 4: 8 - 19

6.3.3 Northridge, CA bridges only scenario

In this scenario we are assuming that only bridges were damaged. This situation will not affect our methodology. However, the input data for the Steiner tree is different in comparison with the data that we used in the worst case scenario. The main difference is that instead of having 528 bidirectional roads we had 224 bidirectional roads that could be restored.

Figure 87 presents the geographical location of the bridges and essential facilities for the area of interest.

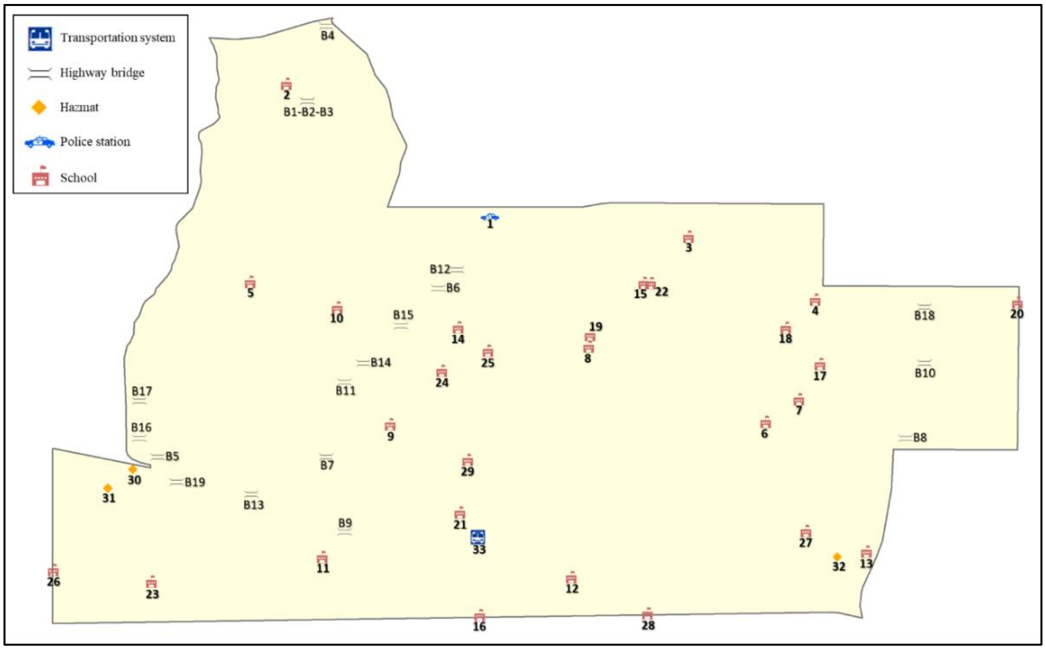


Figure 87. Bridges and essential facilities locations Northridge CA

The Steiner tree solution for priority 1 group is presented in Figure 88. As can be observed, the solution included only roads that do not have bridges on them. This means that it is possible to connect all the essential facilities without using any bridges and using 33 roads in working condition.

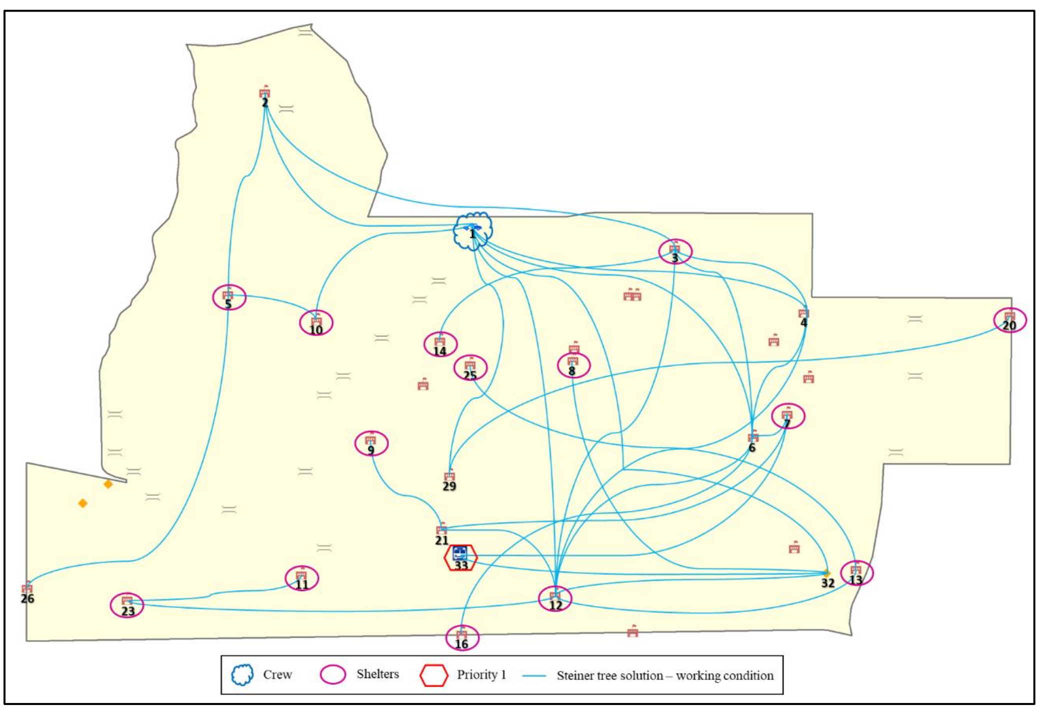


Figure 88. Steiner tree solution for priority 1 – only bridges

6.3.4 Northridge CA bridges and 50% of the remaining roads scenario

We decided to create this scenario because the bridges only scenario did not allow us to use the scheduling formulation. In this scenario we had 375 bidirectional roads that could be restored. As it can be seen in Figure 89, there was no need to fix any roads. All the facilities are connected using 26 roads in working condition.

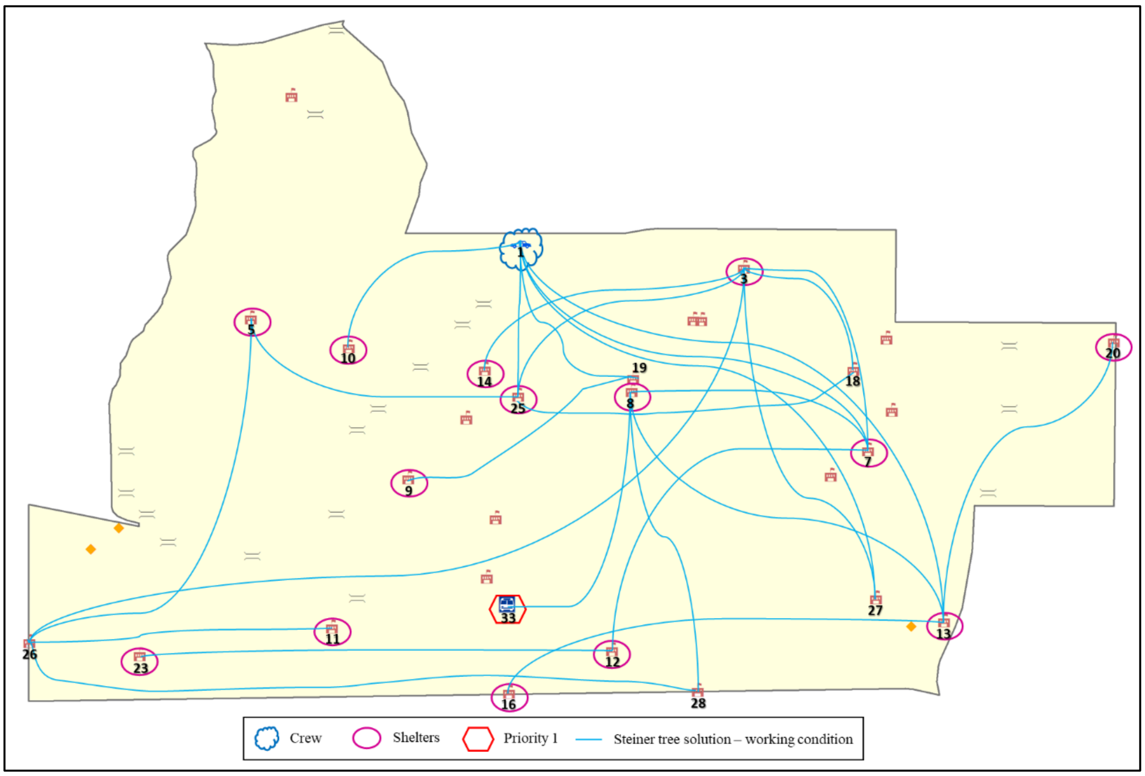


Figure 89. Steiner tree solution for priority 1 – bridges and 50%

6.3.5 Northridge CA 90% scenario – single crew

In this scenario we had 475 bidirectional roads damaged by the earthquake. Figure 90 shows the essential facilities that are part of the priority 1 group.

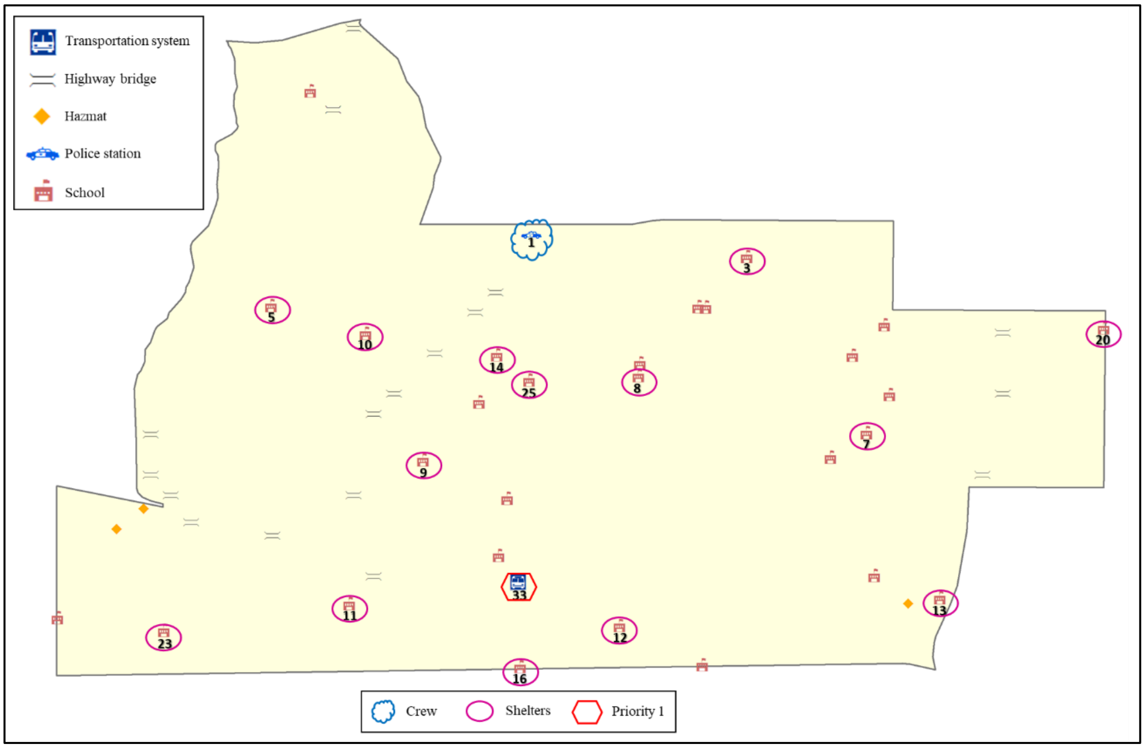


Figure 90. Initial road system for priority 1 – 90% scenario – single crew

As a result of the Steiner tree model solution which is presented in Figure 91, we observed that 5 roads needed to be repaired. It is important to note that 23 working condition roads were also part of the solution.

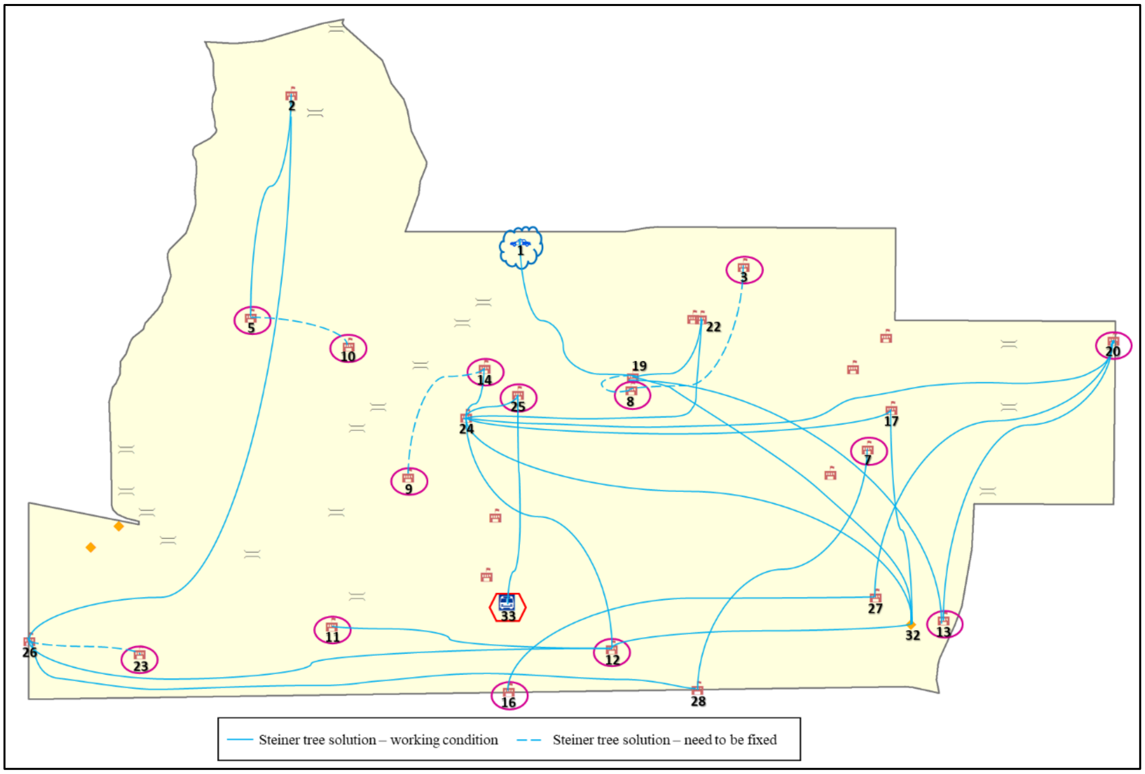


Figure 91. Steiner tree solution for priority 1 – 90% scenario – single crew

The one-to-one mapping required for the scheduling model is presented in Figure 92. In addition, the schedule solution is presented in Figure 93. The final restored system for priority 1 group, which is the initial point for the priority 2 group, was presented in Figure 94.

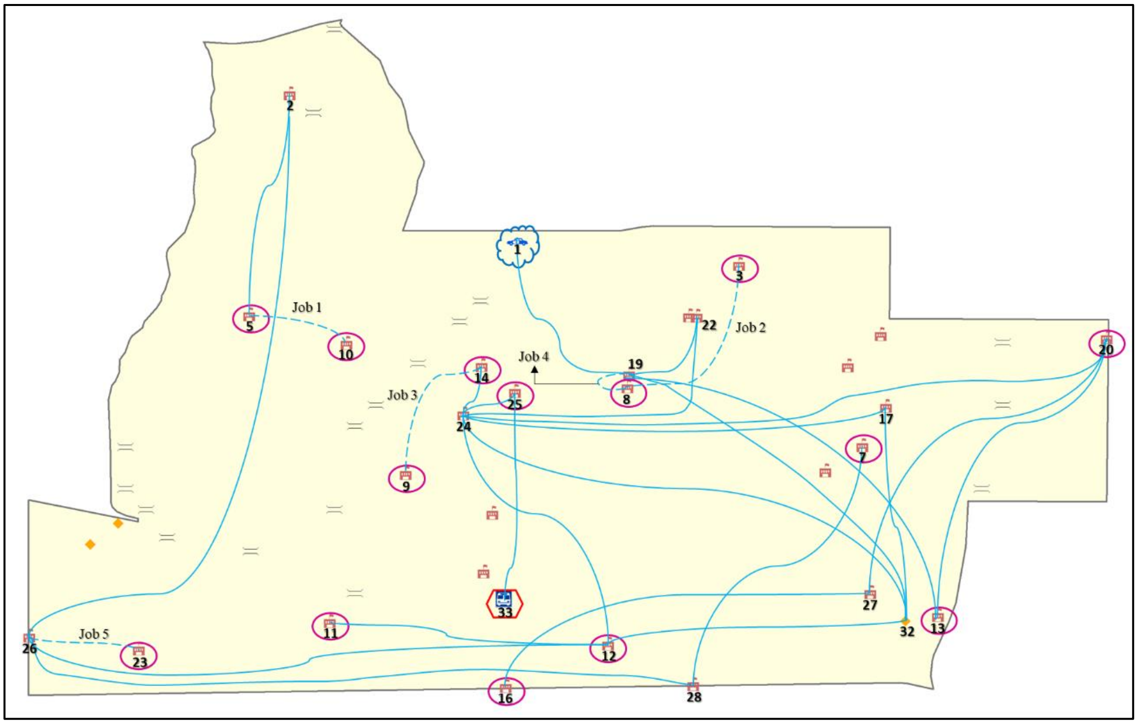


Figure 92. Jobs to schedule for priority 1 – 90% scenario – single crew

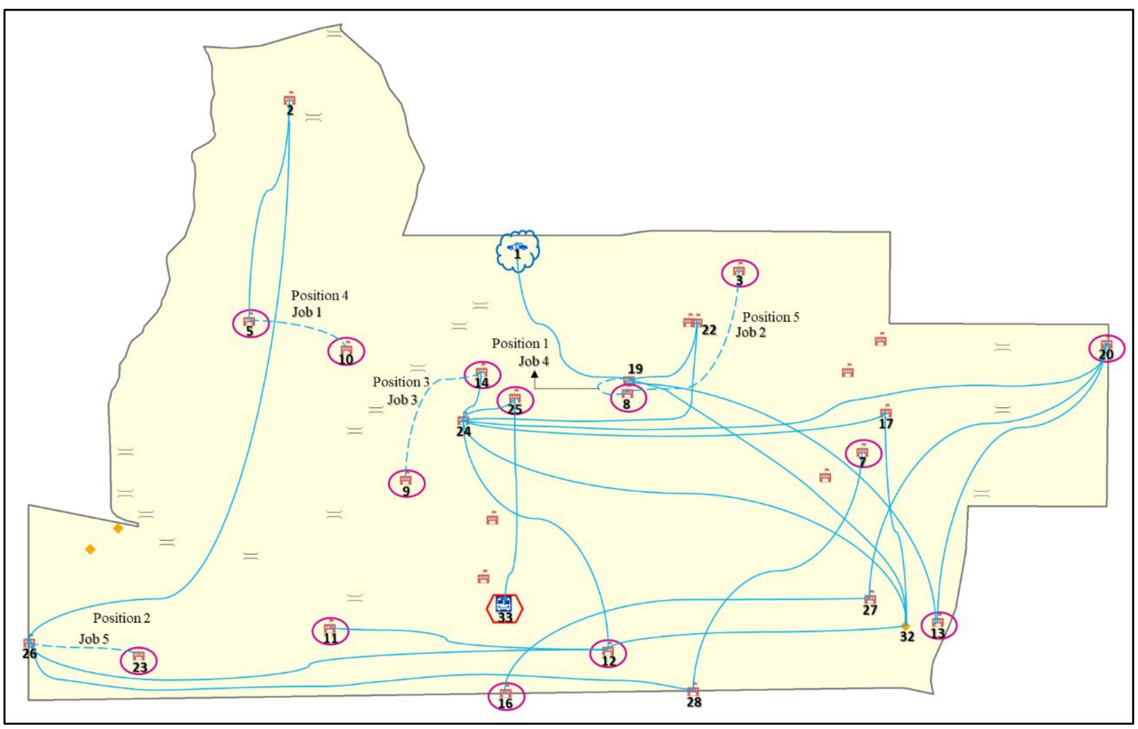


Figure 93. Crew's schedule for priority 1 – 90% scenario – single crew

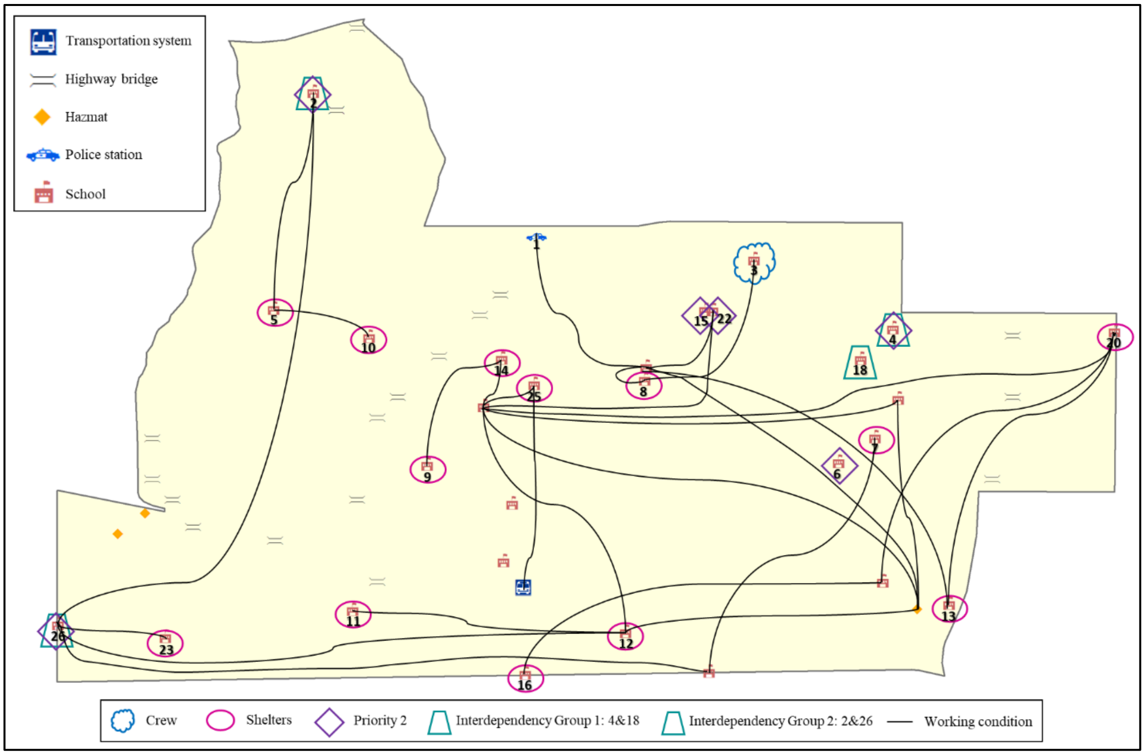


Figure 94. Initial road system for priority 2 – 90% scenario – single crew

The Steiner tree solution for priority 2 group is presented in Figure 95. Checking the interdependency groups, we observed that in a partial way both groups were addressed in this priority. It was necessary to re-run the Steiner tree model including facility 18 as part of priority 2 group. The updated Steiner tree solution is presented in Figure 96. The number of roads that needed to be fixed is the same in both cases, which is two. The mapping and final schedule were presented in Figure 97 and Figure 98, respectively.

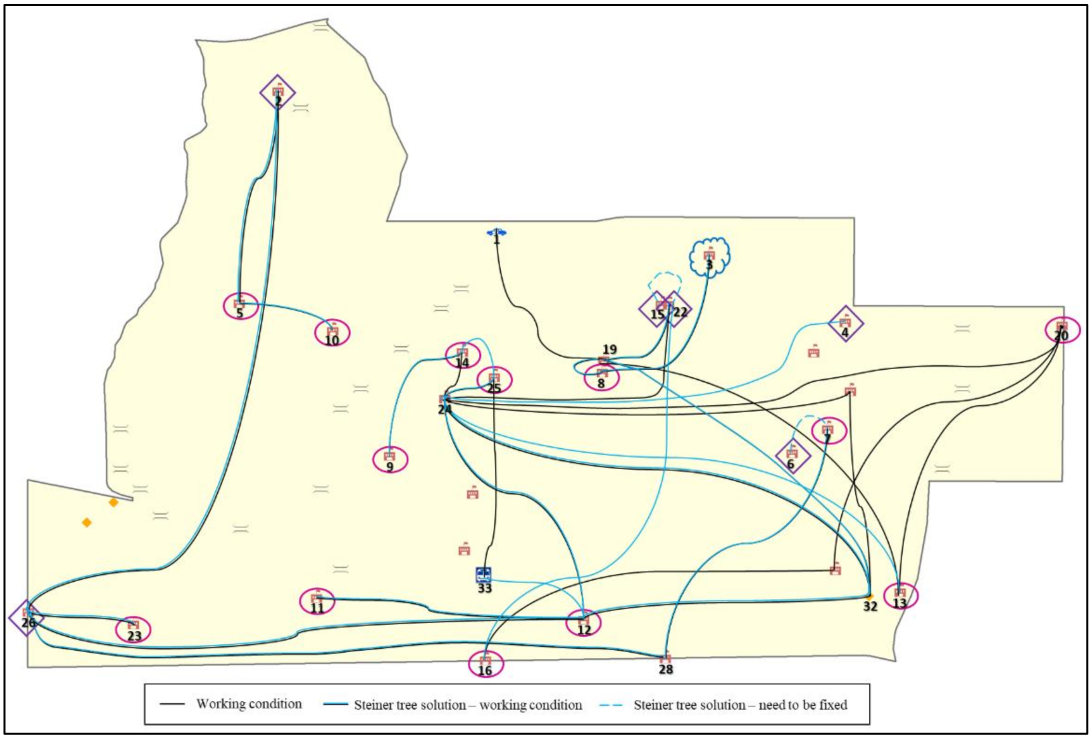


Figure 95. Steiner tree solution for priority 2 – 90% scenario – single crew

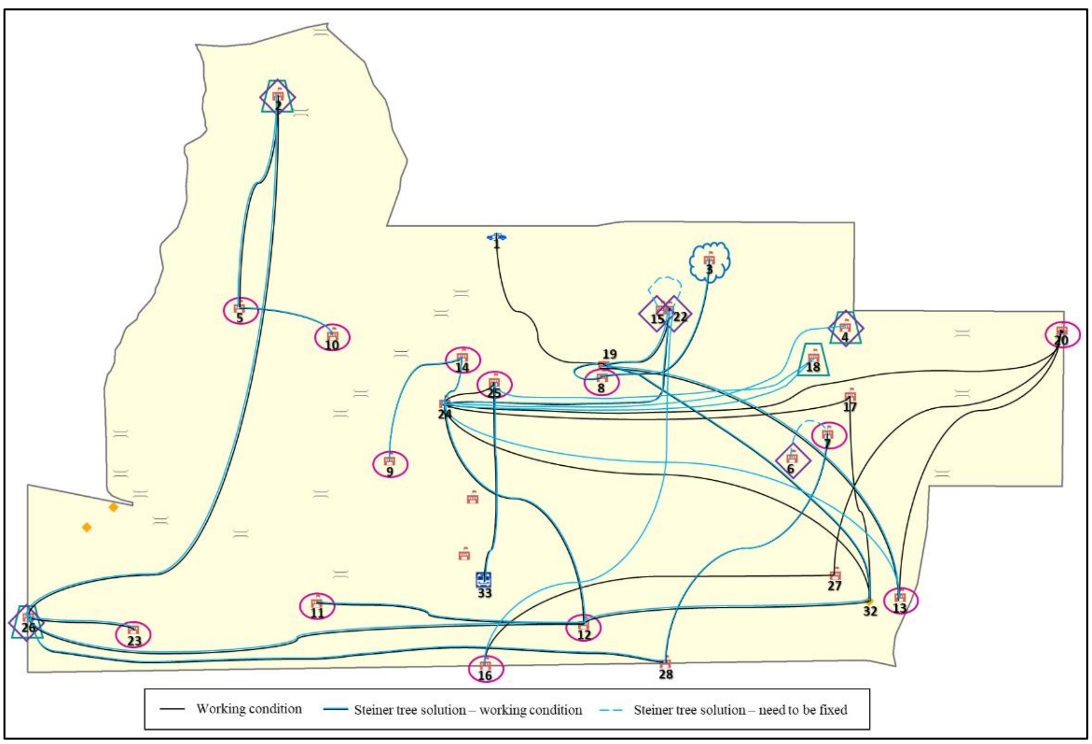


Figure 96. Steiner tree solution for priority 2 with interdependencies – 90% scenario – single crew

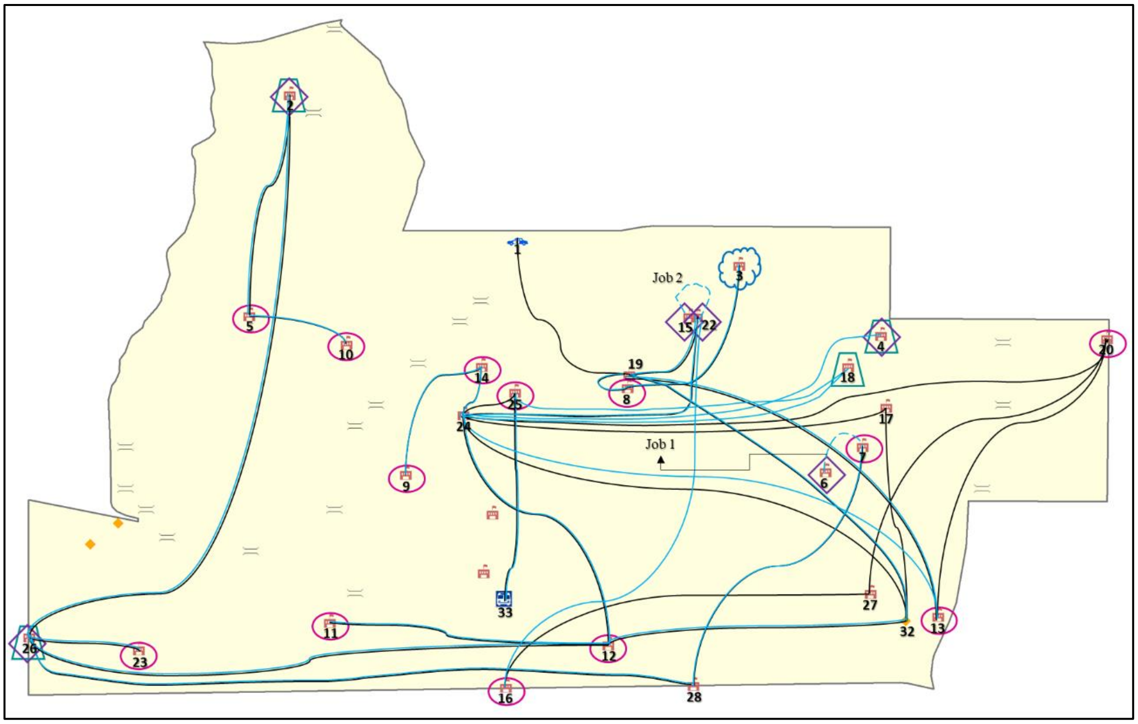


Figure 97. Jobs to schedule for priority 2 – 90% scenario – single crew

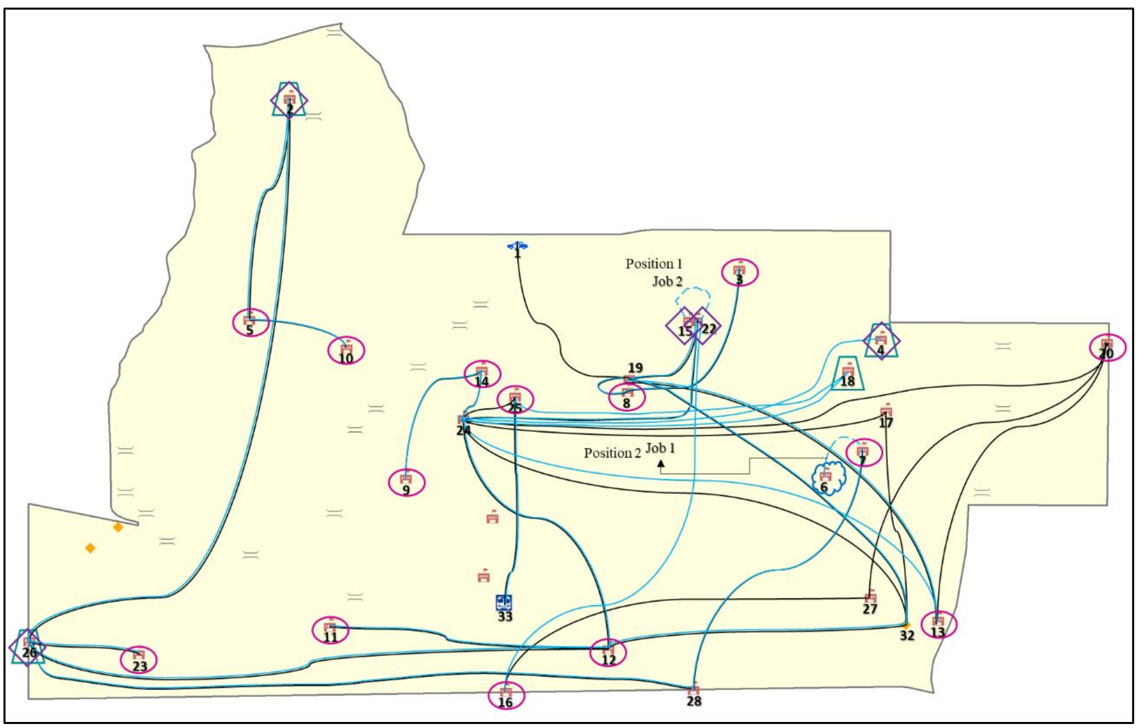


Figure 98. Crew's schedule for priority 2 - 90% scenario – single crew

The updated system which is the starting point for priority 3 group was presented in Figure 99. The Steiner tree solution (Figure 100) showed that only one road needed to be repaired.

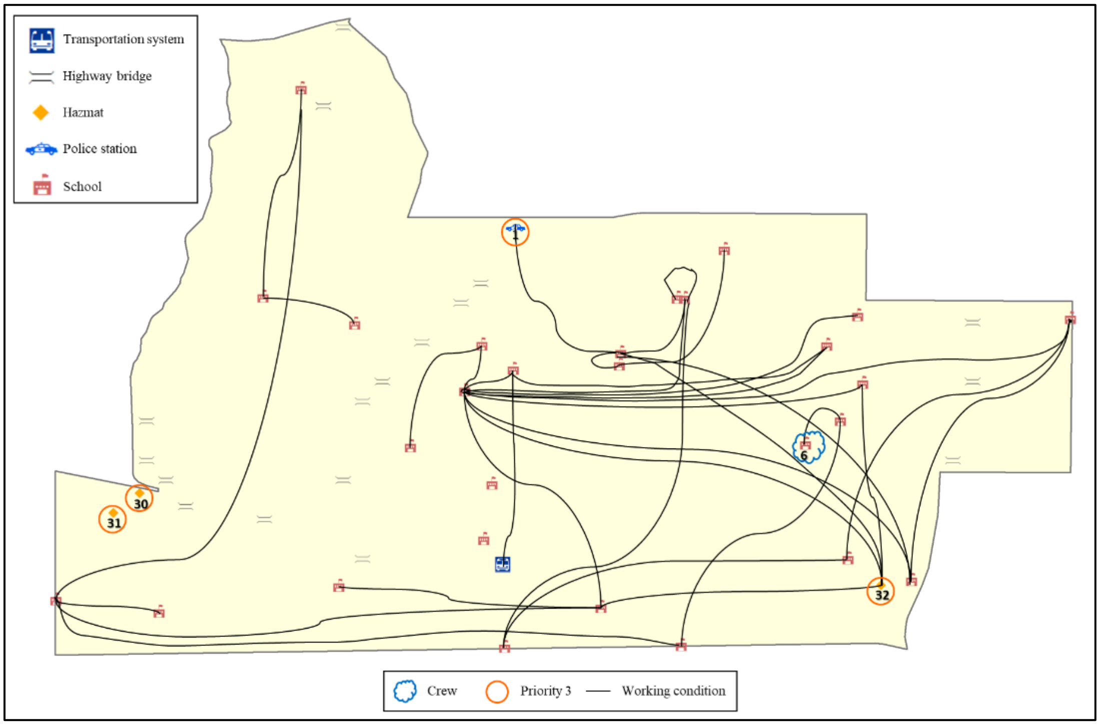


Figure 99. Initial road system for priority 3 – 90% scenario – single crew

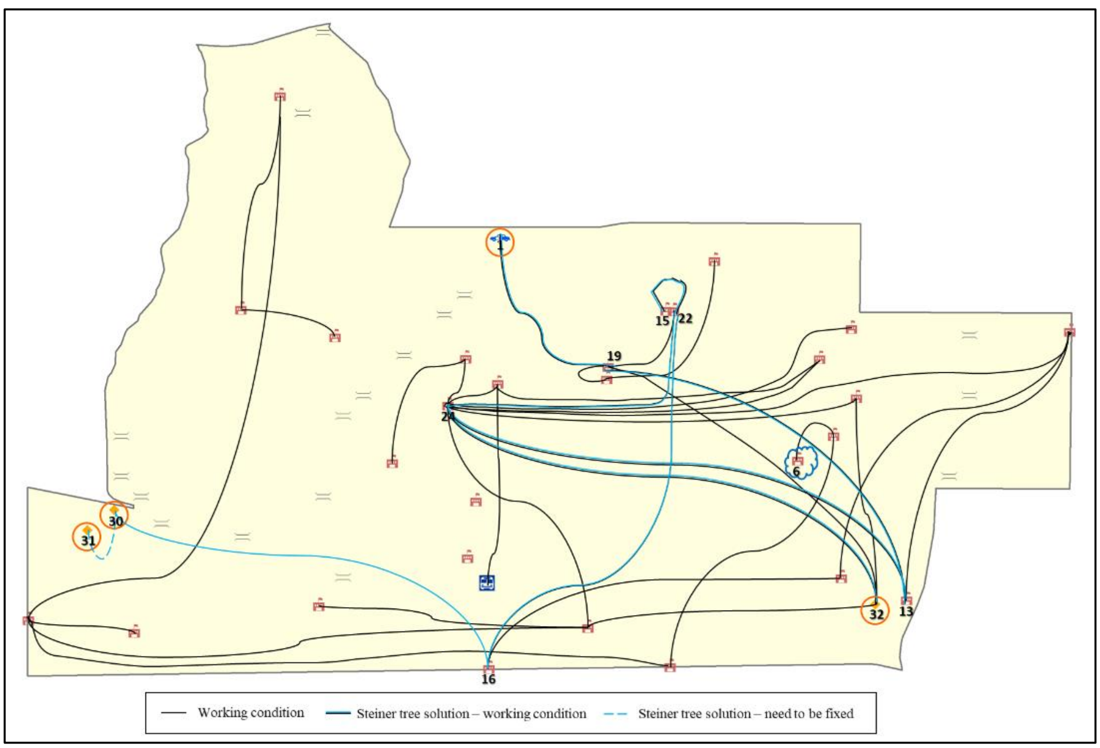


Figure 100. Steiner tree solution for priority 2 – 90% scenario – single crew

Figure 101 presented the starting point for the facilities with non-priority. As can be observed in Figure 102, the Steiner tree solution showed that no roads needed to be fixed.

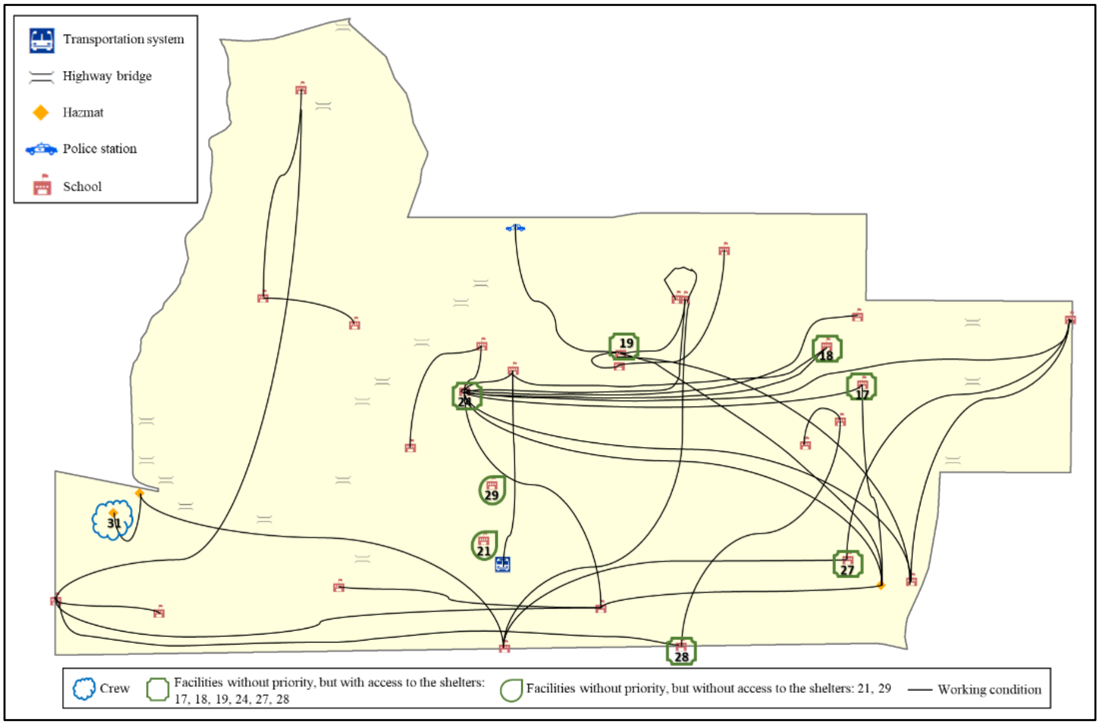


Figure 101. Initial road system for facilities with non-priority – 90% scenario – single crew

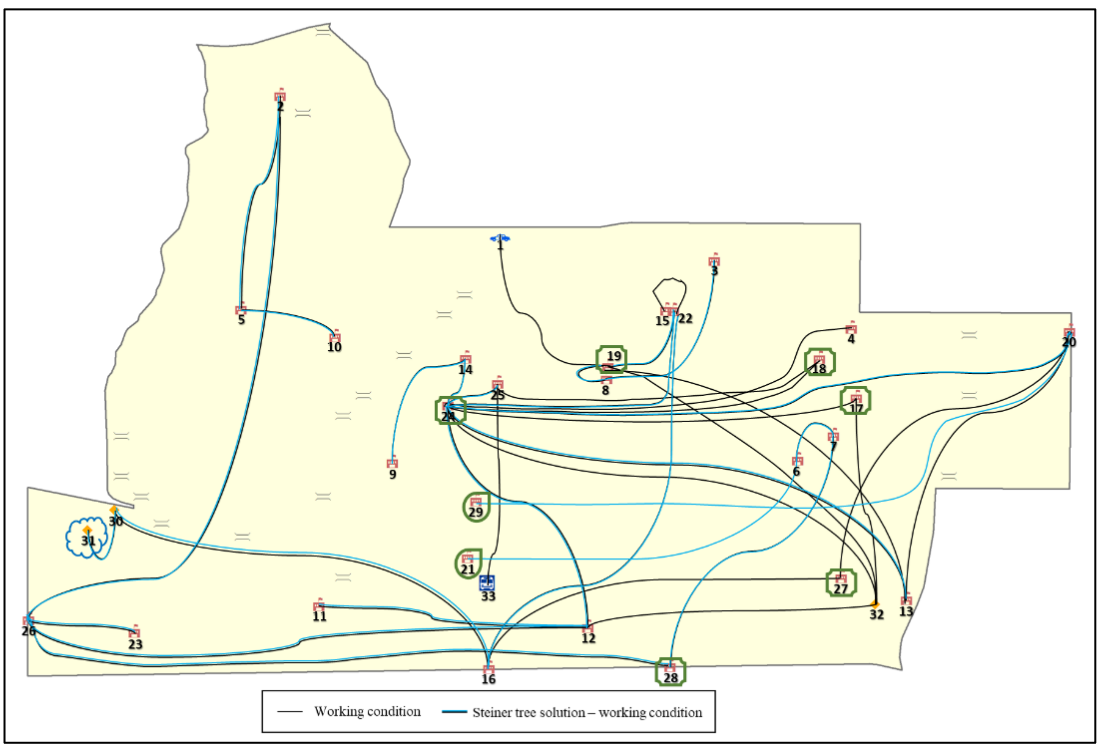


Figure 102. Steiner tree solution for facilities with non-priority – 90% scenario – single crew

The final infrastructure system that needs to be used to connect all the essential facilities is presented in Figure 103.

A summary of the crew's scheduling was presented in Figure 104. For this scenario it was necessary to restore 8 (1.68%) roads.

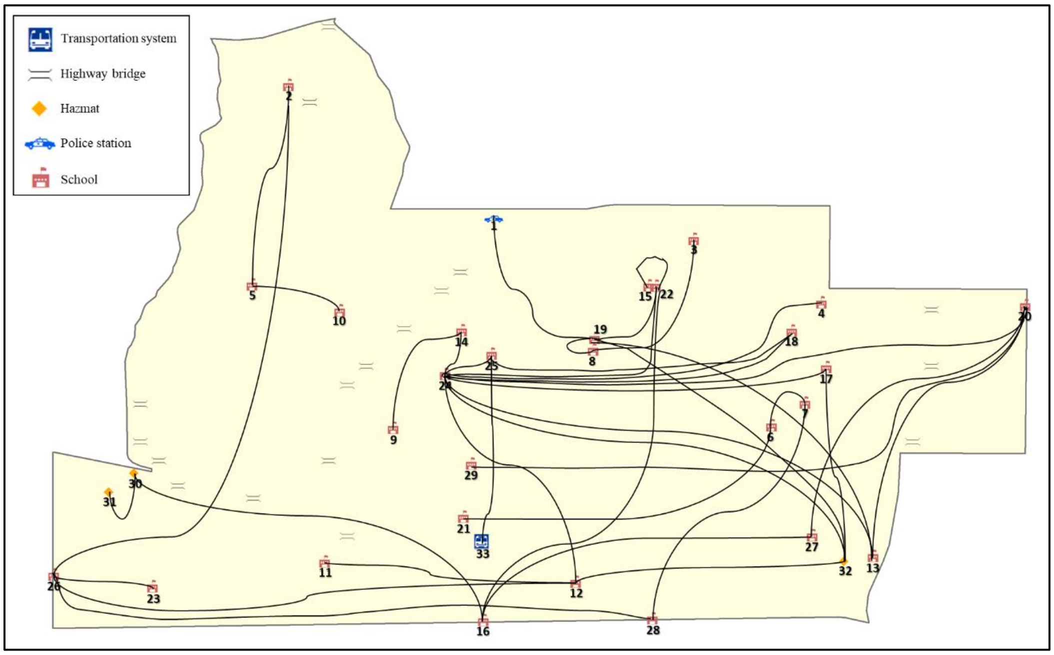


Figure 103. Final restored road infrastructure system – 90% scenario – single crew

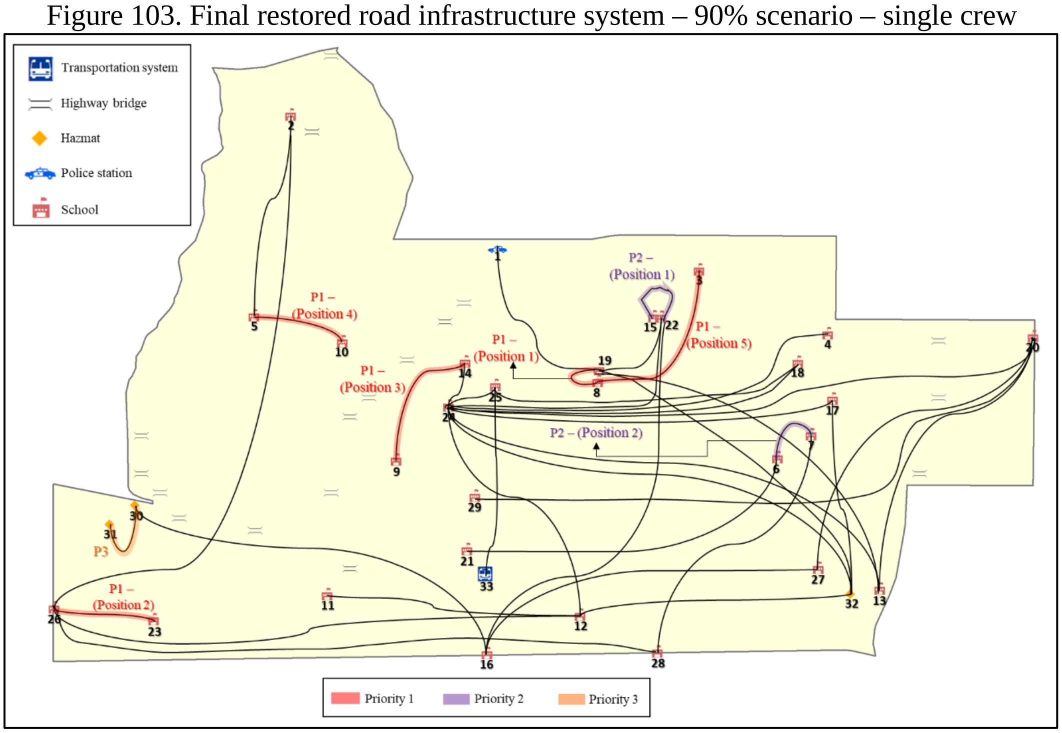


Figure 104. Final crew's schedule by priority groups - 90% scenario – single crew

6.4 Scenarios results comparison

As it was expected the worst case scenarios, single and multiple crews, required the highest number or roads to be fixed. Therefore, the reconstruction time in these worst case scenarios is also the highest. Table 26 and Table 27 presented a summary of the main scenarios' results.

Table 26. Comparison of scenarios – roads condition

Scenarios	Roads condition	Priorities			
		Priority 1	Priority 2	Priority 3	No priority
Worst case - single crew	Working	0	15	12	18
	Fixed	16	7	3	6
	Total	16	22	15	24
Worst case – multiple crews	Working	0	15	13	19
	Fixed	16	7	3	6
	Total	16	22	16	25
90%	Working	23	24	8	24
	Fixed	5	2	1	0
	Total	28	26	9	24
Only bridges	Working	33	-	-	-
	Fixed	0	-	-	-
	Total	33	-	-	-
Bridges and 50%	Working	27	-	-	-
	Fixed	0	-	-	-
	Total	27	-	-	-

Table 27. Comparison of scenarios – reconstruction time

Priorities	Scenarios reconstruction time (days)				
	Worst case - single crew	Worst case – multiple crews	90%	Only bridges	Bridges and 50%
Priority 1	730.1	392	200.9	0	0
Priority 2	181.3	134	24.5	-	-
Priority 3	78.4	64	14.7	-	-
No priority	191.1	118	0	-	-

VII. SUMMARY, RESEARCH CONTRIBUTIONS, AND FUTURE WORK

After a disaster strikes, the road infrastructure system can be damaged or blocked by debris. Due to this, the accessibility to essential facilities such as hospitals, shelters, police stations, and fire stations is compromised. To overcome a road infrastructure emergency, it is necessary to invest a substantial amount of money. For instance, in Colombia, 91% of the annual road infrastructure system investment goes to rehabilitation (Invias, 2009).

A literature review in quantitative model application in humanitarian logistics was done. As a result of the review, we were able to conclude that there is a need for additional research in the recovery activity, specifically in debris management and restoration of affected infrastructure. Our conclusion was reinforced by Matsumaru et al. (2012), Altay and Green (2006), Galindo and Batta (2013), and Habib et al. (2016).

This research focused on the post-disaster phase, specifically on recovery activity related to road infrastructure. The developed methodology and mathematical models address scheduling and network design decisions allowing emergency managers to identify the roads that need to be restored considering interdependencies and priorities among the essential facilities that need to be connected. The optimal schedule for restoring the roads, including the crews' assignment, is also provided.

The methodology included a 2-stage process. The first stage identified the list of roads to be scheduled for the restoration process. To do that, we used a Steiner Tree Formulation that determined the set of roads needed to connect all the facilities in a given priority group, with the minimum possible time to restore the damaged roads. We adapted the Steiner Tree Formulation presented by Goemans and Myung (1993).The second stage created the optimal schedule of the jobs and the crew that will oversee the restoration process for each road. The proposed Scheduling algorithm determines the sequence in which the roads need to be restored and the crew assignment to minimize the total completion time for the restoration process. We developed a single crew formulation and a multiple crew formulation for the Scheduling optimization model. In this model, we used the ideas presented by French (1982) and Mokoto (1999). The two-stage process needs to be executed for every priority group and one last time for the remaining facilities. The key idea is to update the condition of the road network at the end of each iteration and use it as an initial condition for the next one.

To demonstrate the application of our models and methodology, we replicated the 1994 Northridge, CA earthquake and generated disaster scenarios using Hazus, which is a tool developed by the Federal Emergency Management Agency (FEMA). Hazus estimates potential losses for buildings and infrastructures as well as the impacts of earthquakes, hurricane winds, and floods on a given population (2017). Data related to the impact of the earthquake on the transportation network and the essential facilities affected were extracted from the simulation. In addition, the distances and possible paths among facilities were determined using Google maps.

The finished work expands the body of knowledge that could help emergency managers, government, and communities to make efficient use of reconstruction budgets and resources while serving the affected population. In addition, the methodology that supports scheduling and network design decisions and the consideration of priorities, dynamic resources and interdependencies are the main contributions of this dissertation. As a complement, we developed an approach to generate disaster scenarios cases using Hazus.

As a future research opportunity, we believe that testing different objective functions in the scheduling model, such as maximizing the amount of people that can have access to essential facilities, could be useful to complement our methodology. As a complement, it would be interesting to evaluate if the methodology developed could help to measure the resilience of the road infrastructure system. On the other hand, considering other sources of information such as SABER (Single Automated Business Exchange for Reporting) and social media posts will help to determine the interdependencies and priorities groups in a more objective way. Moreover, using the models and methodology, perhaps a decision support system could be explored. Also, it would be interesting to compare the results obtained using our methodology with the real decisions that were made in the reconstruction process of Northridge California after the 1994 earthquake.

Finally, we believe that there may be an opportunity to improve our methodology. Right now, our methodology connects the priorities groups and updates the condition of the road network at the end of each iteration and uses it as an initial condition for the next one. We find the optimal solution for each priority group. However, the solution may be improved by including the decisions that need to be made in the following priority groups while solving the priority group at hand. Thus, the final solution would be optimal for the whole problem instead of just for each priority group By implementing Nested Optimization approach using the work of Hadjipieris and Bishop (2016) as a reference, we are positive that this objective could be achieved. The general idea behind Nested Optimization is to take a problem and divide it into smaller pieces which are then solved through multiple methods. The result is that solutions are realized that both solve the larger problem and its subparts.

REFERENCES

1. Adivar, B., & Mert, A. (2010). International disaster relief planning with fuzzy credibility Fuzzy Optimization and Decision Making, 9(4), 413-433.

2. Ajam, M., Akbari, V., & Salman, S. (2019). Minimizing latency in post-disaster road clearance operations. European Journal of Operational Research, 277(3), 1098-1112. doi:10.1016/j.ejor.2019.03.024

3. Akbari, V., & Salman, F. S. (2017). Multi-vehicle synchronized arc routing problem to restore post-disaster network connectivity. European Journal of Operational Research, 257(2), 625-640. doi:10.1016/j.ejor.2016.07.043

4. Altay, N., & Green, W. G. (2006). OR/MS research in disaster operations management. European Journal of Operational Research, 175(1), 475–493. doi:10.1016/j.ejor.2005.05.016

5. Bagchi, A., Aliyas, P. J., & Maloni, M. (2011). Improving bid efficiency for humanitarian food aid procurement. International Journal of Production Economics, 134(1), 238-245. doi:10.1016/j.ijpe.2011.07.004

6. Balcik, B., & Beamon, B. M. (2008). Facility location in humanitarian relief International Journal of Logistics-Research and Applications, 11(2), 101-121.

7. Balcik, B., Beamon, B. M., & Smilowitz, K. (2008). Last mile distribution in humanitarian relief Journal of Intelligent Transportation Systems, 12(2), 51-63. doi:10.1080/15472450802023329

8. Beamon, B. M., & Kotleba, S. A. (2006). Inventory modelling for complex emergencies in humanitarian relief operations. International Journal of Logistics: Research & Applications, 9(1), 1-18.

9. Ben-Tal, A., Chung, B. D., & Mandala, S. R. (2011). Robust optimization for emergency logistics planning: Risk mitigation in humanitarian relief supply chains. Transportation Resarch Part B, 45(8), 1177-1189. doi:10.1016/j.trb.2010.09.002

10. Brooks, J. D., Kar, K., & Mendonca, D. (2013). Dynamic allocation of entities in closed queueing networks: An application to debris removal. Paper presented at the 2013 IEEE International Conference on Technologies for Homeland Security, HST 2013.

11. Campos, A., Holm-Nielsen, N., Diaz, C., Rubiano, D., Costa, C., Ramirez, F., & Dickson, E. (2012). Analisis de la gestion del riesgo de desastres en Colombia: un aporte para la construccion de politicas publicas. Bogota, Colombia: Banco Mundial.

12. Centre for Research on the Epidemiology of Disasters - CRED. (2015). The human cost of natural disasters 2015: a global perspective. Retrieved December 15, 2019, from http://cred.be/sites/default/files/The_Human_Cost_of_Natural_Disasters_CRED.pdf

13. Charles, A., & Lauras, M. (2011). An enterprise modelling approach for better optimisation modelling: application to the humanitarian relief chain coordination problem OR Spectrum, 33(3), 815-841. doi:10.1007/s00291-011-0255-2

14. Coppola, D. P. (2011). Introduction to International Disaster Management, 2nd Edition: Elsevier

15. Cruz, F. R. B., & MacGregor Smith, J. (2007). Approximate analysis of M/G/c/c state-dependent queueing networks. Computers & Operations Research, 34(8), 2332-2344. doi:10.1016/j.cor.2005.09.006

16. De Groeve, T., Vernaccini, L., & Poljansek, K. (2016). Index for Risk Management - INFORM. Concept and Methodology. Retrieved from

17. Duran, S., Gutierrez Marco, A., & Keskinocak, P. (2011). Pre-Positioning of Emergency Items for CARE International Interfaces, 41(3), 223-237. doi:10.1287/inte.1100.0526

18. Ertem, M. A., Buyurgan, N., & Rossetti, M. D. (2010). Multiple-buyer procurement auctions framework for humanitarian supply chain management International Journal of Physical Distribution & Logistics Management, 40(3), 202-227. doi:10.1108/09600031011035092

19. Federal Emergency Management Agency. (2017). HAZUS-MH (Multi-Hazard).

20. French, S. (1982). Sequencing and scheduling: An introduction to the mathematics of the job-shop: Ellis Horwood Limited.

21. Fritz, L., & Noon, T. (2017). Caterpillar Jobsite Information Study. Retrieved December 15, 2019, from https://www.westrac.com.au/-/media/Project/Westrac/Mainsite/white-papers/document-cat-connect-white-paper-productivity-52019.pdf

22. Galindo, G., & Batta, R. (2013). Review of recent developments in OR/MS research in disaster operations management. European Journal of Operational Research, 230(2), 201-211. doi:10.1016/j.ejor.2013.01.039

23. Geroliminis, N., Karlaftis, M. G., & Skabardonis, A. (2009). A spatial queuing model for the emergency vehicle districting and location problem. Transportation Research Part B: Methodological, 43(7), 798-811. doi:10.1016/j.trb.2009.01.006

24. Gibbons, D. E., & Subhashish, S. (2009). Designing Referral Network Structures and Decision Rules to Streamline Provision of Urgent Health and Human Services Decision Sciences, 40(2), 351-371. doi:10.1111/j.1540-5915.2009.00230.x

25. Goemans, M. X., & Myung, Y.-S. (1993). A catalog of steiner tree formulations. Networks, 23(1), 19-28.

26. Gormez, N., Koksalan, M., & Salman F., S. (2011). Locating disaster response facilities in Istanbul Journal of the Operational Research Society, 62(7), 1239-1252.

27. Guha-Sapir, D., Below, R., & Hoyois, P. (2017). EM-DAT: The CRED/OFDA International Disaster Database. from Université Catholique de Louvain – Brussels – Belgium

28. Habib, M. S., Lee, Y. H., & Memon, M. S. (2016). Mathematical Models in Humanitarian Supply Chain Management: A Systematic Literature Review. Mathematical Problems in Engineering, 2016, 20. doi:10.1155/2016/3212095

29. Hadjipieris, P., & Bishop, S. (2016). Nested Optimization - A Practical Approach Delivering Increased Production. Society of Petroleum Engineers. doi:10.2118/181372-MS

30. Halper, R., & Raghavan, S. (2011). The Mobile Facility Routing Problem. Transportation Science, 45(3), 413-434. doi:10.1287/trsc.1100.0335

31. Huang, M., Smilowitz, K., & Balcik, B. (2012). Models for relief routing: Equity, efficiency and efficacy Transportation Research Part E-Logistics and Transportation, 48(1), 2-18. doi:10.1016/j.tre.2011.05.004

32. Hwang, S., Park, M., Lee, H.-S., Lee, S., & Kim, H. (2015). Postdisaster Interdependent Built Environment Recovery Efforts and the Effects of Governmental Plans: Case Analysis Using System Dynamics. Journal of Construction Engineering and Management, 141(3). doi:10.1061/(asce)co.1943-7862.0000939

33. Iannoni, A. P., & Morabito, R. (2007). A multiple dispatch and partial backup hypercube queuing model to analyze emergency medical systems on highways. Transportation Research Part E: Logistics and Transportation Review, 43(6), 755-771. doi:10.1016/j.tre.2006.05.005

34. International Federation of Red Cross and Red Crescent Societies. (2010). World Disasters Report 2010: Focus on urban risk. Retrieved December 15, 2019, https://www.ifrc.org/Global/Publications/disasters/WDR/WDR2010-full.pdf

35. Invias. (2009). Informe presupuestal de la Oficina de Prevencion y Atencion de Emergencias. Colombia. Retrieve December 15, 2019, from https://www.invias.gov.co/index.php

36. Kovács, G., & Spens, K. (2007). Humanitarian logistics in disaster relief operations. International Journal of Physical Distribution & Logistics Management, 37(2), 99-114. doi:10.1108/09600030710734820

37. Larson, R. C. (1974). A hypercube queuing model for facility location and redistricting in urban emergency services. Computers & Operations Research, 1(1), 67-95. doi:10.1016/0305-0548(74)90076-8

38. MacGregor Smith, J. (1991). State-dependent queueing models in emergency evacuation networks. Transportation Research Part B: Methodological, 25(6), 373-389. doi:10.1016/0191-2615(91)90031-D

39. Manopiniwes, W., & Irohara, T. (2017). Stochastic optimisation model for integrated decisions on relief supply chains: preparedness for disaster response. International Journal of Production Research, 55(4), 979-996.

40. Marianov, V., & ReVelle, C. (1996). The Queueing Maximal availability location problem: A model for the siting of emergency vehicles. European Journal of Operational Research, 93(1), 110-120. doi:10.1016/0377-2217(95)00182-4

41. Matsumaru, R., Nagami, K., & Takeya, K. (2012). Reconstruction of the Aceh Region following the 2004 Indian Ocean tsunami disaster: A transportation perspective. IATSS Research, 36(1), 11-19. doi:10.1016/j.iatssr.2012.07.001

42. McCoy, J., & Brandeau, M. (2011). Efficient stockpiling and shipping policies for humanitarian relief: UNHCR's inventory challenge. OR Spectrum, 33(3), 673-698. doi:10.1007/s00291-011-0237-4

43. Mete, H. O., & Zabinsky, Z. B. (2010). Stochastic optimization of medical supply location and distribution in disaster management. International Journal of Production Economics, 126(1), 76-84. doi:10.1016/j.ijpe.2009.10.004

44. Ministerio de Transporte. (2011). Programa Infraestructura para la Prosperidad 2010-2014. Colombia. Retrieve December 15, 2019, from https://www.mintransporte.gov.co/

45. Mohan, S., Gopalakrishnan, M., & Mizzi, P. J. (2011). Improving the efficiency of a non-profit supply chain for the food insecure. International Journal of Production Economics, 143(2), 248-255. doi:10.1016/j.ijpe.2011.05.019

46. Mokoto, E. (1999). Scheduling to minimize the makespan on identical parallel Machines: an LP-based algorithm. Investigacion Operative, 97-107.

47. Moreno, A., Munari, P., & Alem, D. (2019). A branch-and-Benders-cut algorithm for the Crew Scheduling and Routing Problem in road restoration. European Journal of Operational Research, 275(1), 16-34. doi:10.1016/j.ejor.2018.11.004

48. Nagurney, A., Yu, M., & Qiang, Q. (2011). Supply chain network design for critical needs with outsourcing. Papers in Regional Science, 90(1), 123-142. doi:10.1111/j.1435-5957.2010.00317.x

49. Nurre, S. G., Cavdaroglu, B., Mitchell, J. E., Sharkey, T. C., & Wallace, W. A. (2012). Restoring infrastructure systems: An integrated network design and scheduling (INDS) problem. European Journal of Operational Research, 223(3), 794-806. doi:10.1016/j.ejor.2012.07.010

50. Ortuño M., T., Tirado, G., & Vitoriano, B. (2011). A lexicographical goal programming based decision support system for logistics of Humanitarian Aid TOP, 19(2), 464-479. doi:10.1007/s11750-010-0138-8

51. Paulsen, G. C., & Cangelosi, J. P. (1994). Disaster planning. Outlook, 61(4), 35.

52. Phillips, B. D. (2005). Disaster as a Discipline: The Status of Emergency Management Education in the U.S. International Journal of Mass Emergencies and Disasters, 23(1), 11-140.

53. Ransikarbum, K., & Mason, S. J. (2016). Goal programming-based post-disaster decision making for integrated relief distribution and early-stage network restoration. International Journal of Production Economics, 182, 324-341. doi:10.1016/j.ijpe.2016.08.030

54. Rottkemper, B., Fischer, K., & Blecken, A. (2011). Inventory relocation for overlapping disaster settings in humanitarian operations OR Spectrum, 33(3), 721-749. doi:10.1007/s00291-011-0260-5

55. Sanci, E., & Daskin, M. (2019). Integrating location and network restoration decisions in relief networks under uncertainty. European Journal of Operational Research, 279(2), 335-350. doi:10.1016/j.ejor.2019.06.012

56. Sharkey, T. C., Nurre, S. G., Nguyen, H., Chow, J. H., Mitchell, J. E., & Wallace, W. A. (2016). Identification and classification of restoration interdependencies in the wake of Hurricane Sandy. Journal of Infrastructure Systems., 22(1). doi:10.1061/(ASCE)IS.1943-555X.0000262

57. Silva, F., & Serra, D. (2007). Locating emergency services with different priorities: the priority queuing covering location problem. J Oper Res Soc, 59(9), 1229-1238. doi:10.1057/palgrave.jors.2602473

58. Stepanov, A., & Smith, J. M. (2009). Multi-objective evacuation routing in transportation networks. European Journal of Operational Research, 198(2), 435-446. doi:10.1016/j.ejor.2008.08.025

59. Takeda, R. A., Widmer, J. A., & Morabito, R. (2007). Analysis of ambulance decentralization in an urban emergency medical service using the hypercube queueing model. Computers & Operations Research, 34(3), 727-741. doi:10.1016/j.cor.2005.03.022

60. Talebi, K., & Smith, J. M. (1985). Stochastic network evacuation models. Computers & Operations Research, 12(6), 559-577. doi:10.1016/0305-0548(85)90054-1

61. Taskin, S., & Lodree, E. J. J. (2011). A Bayesian decision model with hurricane forecast updates for emergency supplies inventory management Journal of the Operational Research Society, 62(6), 1098-1108.

62. Thomas, A. S., & Kopczak, L. R. (2005). From Logistics to Supply Chain Management: The path forward in the humanitarian sector. Retrieved December 15, 2019, from http://www.fritzinstitute.org/PDFs/WhitePaper/FromLogisticsto.pdf

63. Tinguaro Rodriguez, J., Vitoriano, B., & Montero, J. (2010). A natural-disaster management DSS for Humanitarian Non-Governmental Organisations. Knowledge-Based Systems, 23(1), 17-22. doi:10.1016/j.knosys.2009.07.009

64. Trestrail, J., Jomon, P., & Maloni, M. (2009). Improving bid pricing for humanitarian logistics. International Journal of Physical Distribution & Logistics Management, 39(5), 428-441. doi:10.1108/09600030910973751

65. Tricoire, F., Graf, A., & Gutjahr, W. J. (2012). The bi-objective stochastic covering tour problem Computers & Operations Research, 39(7), 1582-1592. doi:10.1016/j.cor.2011.09.009

66. Ukkusuri, S. V., & Yushimito, W. F. (2008). Location Routing Approach for the Humanitarian Prepositioning Problem. Transportation Research Record, 2089(1), 18-25.

67. United Nations. (2009). UNISDR Terminology on Disaster Risk Reduction. Retrieved December 15, 2019, from https://www.unisdr.org/we/inform/publications/7817

68. Vitoriano, B., Ortuño, M. T., & Tirado, G. (2011). A multi-criteria optimization model for humanitarian aid distribution Journal of Global Optimizatioin, 51(2), 189-208. doi:10.1007/s10898-010-9603-z

69. Wein, L. M., Craft, D. L., & Kaplan, E. H. (2003). Emergency response to an anthrax attack. Proceedings of the National Academy of Sciences, 100(7), 4346-4351. doi:10.1073/pnas.0636861100

APPENDICES

Appendix 1 – Table 14. Damaged bridges part of the shortest paths in Northridge CA

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA004228-CA000037						1		1				1							
CA005517-CA000037						1						1							
CA005519-CA000037			1										1						
CA008970-CA000037						1						1							
CA011783-CA000037						1						1							
CA012393-CA000037					1														
CA012395-CA000037						1						1							
CA001715-CA000037					1														
CA001718-CA000037					1														
CA000019-CA000037						1						1							
CA003887-CA003643								1											
CA005514-CA003643								1											
CA005515-CA003643								1											
CA005516-CA003643								1											
CA005517-CA003643														1					
CA005519-CA003643		1																	
CA005520-CA003643														1					
CA005528-CA003643								1											
CA008970-CA003643								1											

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA009964-CA003643								1											
CA010103-CA003643														1					
CA010337-CA003643								1											
CA010338-CA003643								1											
CA010339-CA003643								1											
CA010640-CA003643				1															
CA011783-CA003643														1					
CA012317-CA003643								1											
CA012393-CA003643					1														
CA012395-CA003643														1					
CA012500-CA003643								1											
CA012654-CA003643								1											
CA012655-CA003643														1					
CA013049-CA003643	1																		
CA001715-CA003643					1														
CA001718-CA003643					1														
CA001723-CA003643								1											
CA000019-CA003643														1					
CA004228-CA003644								1											
CA005517-CA003644								1						1					
CA005518-CA003644								1											
CA005519-CA003644								1					1						
CA012393-CA003644					1			1											
CA012653-CA003644								1											
CA001715-CA003644					1			1											
CA001718-CA003644					1			1											
CA004228-CA003887								1											
CA005518-CA003887								1											

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA005519-CA003887									1										
CA012393-CA003887									1										
CA012653-CA003887									1										
CA013049-CA003887						1						1							
CA001715-CA003887							1												1
CA001718-CA003887							1												1
CA005514-CA004228								1											
CA005515-CA004228								1											
CA005516-CA004228								1											
CA005517-CA004228														1					
CA005519-CA004228		1	1																
CA005520-CA004228														1					
CA005528-CA004228								1											
CA008970-CA004228								1											
CA009964-CA004228								1											
CA010103-CA004228														1					
CA010337-CA004228								1											
CA010338-CA004228								1											
CA010339-CA004228								1											
CA010640-CA004228								1											
CA011783-CA004228														1					
CA012317-CA004228								1											
CA012393-CA004228					1														
CA012395-CA004228														1					
CA012500-CA004228								1											
CA012654-CA004228								1											
CA012655-CA004228														1					
CA013049-CA004228	1																		

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA001715-CA004228					1														
CA001718-CA004228					1														
CA001723-CA004228								1											
CA000019-CA004228														1					
CA005518-CA005514								1											
CA005519-CA005514									1										
CA010640-CA005514										1									
CA012393-CA005514									1										
CA012653-CA005514									1										
CA001715-CA005514							1												1
CA001718-CA005514							1												1
CA005518-CA005515								1											
CA005519-CA005515									1										
CA010640-CA005515										1									
CA012393-CA005515									1										
CA012653-CA005515									1										
CA013049-CA005515						1						1							
CA001715-CA005515							1												1
CA001718-CA005515							1												1
CA005518-CA005516								1											
CA005519-CA005516									1										
CA010640-CA005516										1									
CA012393-CA005516							1												1
CA012653-CA005516								1											
CA001715-CA005516							1												1
CA001718-CA005516							1												1
CA005518-CA005517														1					
CA005519-CA005517							1						1						

Road between facilities	**Uses Bridge ID**																		
	CA022003	**CA022004**	**CA022005**	**CA022124**	**CA023228**	**CA023285**	**CA023303**	**CA023305**	**CA023319**	**CA023323**	**CA023324**	**CA023327**	**CA023355**	**CA023389**	**CA023398**	**CA023686**	**CA023687**	**CA023688**	**CA023846**
CA009964-CA005517								1						1					
CA010640-CA005517								1						1					
CA012317-CA005517								1						1					
CA012393-CA005517							1												1
CA012653-CA005517							1												1
CA013049-CA005517	1													1					
CA001715-CA005517							1												1
CA001718-CA005517							1												1
CA005519-CA005518							1						1	1					
CA005520-CA005518														1					
CA005528-CA005518								1											
CA008970-CA005518								1											
CA009964-CA005518								1											
CA010103-CA005518														1					
CA010337-CA005518								1											
CA010338-CA005518								1											
CA010339-CA005518								1											
CA010640-CA005518								1											
CA011783-CA005518														1					
CA012317-CA005518								1											
CA012393-CA005518							1							1					1
CA012395-CA005518														1					
CA012500-CA005518								1											
CA012653-CA005518											1			1					
CA012654-CA005518														1					
CA012655-CA005518														1					
CA013049-CA005518	1																		
CA001715-CA005518							1							1					1

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA001718-CA005518							1							1					1
CA001723-CA005518								1											
CA000019-CA005518														1					
CA005528-CA005519									1										
CA008970-CA005519											1		1						
CA009964-CA005519								1					1						
CA010337-CA005519									1										
CA010338-CA005519									1										
CA010339-CA005519									1										
CA010640-CA005519									1										
CA011783-CA005519									1										
CA012317-CA005519								1					1						
CA012395-CA005519											1		1						
CA012500-CA005519											1		1						
CA012654-CA005519									1										
CA013049-CA005519	1										1		1	1					
CA001723-CA005519									1										
CA013049-CA005520						1						1							
CA001715-CA005520									1										
CA001718-CA005520									1										
CA012393-CA005528									1										
CA012653-CA005528									1										
CA013049-CA005528						1						1							
CA001715-CA005528									1										
CA001718-CA005528									1										
CA012393-CA008970					1						1								
CA012653-CA008970											1								
CA013049-CA008970						1						1							

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA001715-CA008970							1												1
CA001718-CA008970							1												1
CA012393-CA009964					1			1											
CA012653-CA009964								1											
CA013049-CA009964						1						1							
CA001715-CA009964					1			1											
CA001718-CA009964					1			1											
CA013049-CA010103						1						1							
CA010640-CA010337										1									
CA012393-CA010337									1										
CA012653-CA010337									1										
CA013049-CA010337						1						1							
CA001715-CA010337							1												1
CA001718-CA010337							1												1
CA012393-CA010338									1										
CA012653-CA010338								1											
CA013049-CA010338						1						1							
CA001715-CA010338							1												1
CA001718-CA010338							1												1
CA012393-CA010339							1												1
CA012653-CA010339								1											
CA001715-CA010339							1												1
CA001718-CA010339							1												1
CA012393-CA010640									1										
CA012653-CA010640								1											
CA001715-CA010640					1			1											
CA001718-CA010640							1												1
CA012393-CA011783									1										

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA012653-CA011783									1										
CA013049-CA011783						1						1							
CA001715-CA011783							1												1
CA001718-CA011783							1												1
CA012393-CA012317					1			1											
CA012653-CA012317								1											
CA013049-CA012317						1						1							
CA001715-CA012317					1			1											
CA001718-CA012317					1			1											
CA012395-CA012393					1						1								
CA012500-CA012393					1						1								
CA012654-CA012393									1										
CA013049-CA012393	1				1														
CA001723-CA012393									1										
CA000019-CA012393									1										
CA012653-CA012395											1								
CA013049-CA012395	1													1					
CA001715-CA012395							1												1
CA001718-CA012395							1												1
CA012653-CA012500											1								
CA013049-CA012500						1						1							
CA001715-CA012500							1												1
CA001718-CA012500							1												1
CA012654-CA012653									1										
CA013049-CA012653	1																		
CA001723-CA012653									1										
CA013049-CA012654						1						1							
CA001715-CA012654									1										

Road between facilities	Uses Bridge ID																		
	CA022003	CA022004	CA022005	CA022124	CA023228	CA023285	CA023303	CA023305	CA023319	CA023323	CA023324	CA023327	CA023355	CA023389	CA023398	CA023686	CA023687	CA023688	CA023846
CA001718-CA012654									1										
CA013049-CA012655						1						1							
CA001715-CA013049	1				1														
CA001718-CA013049	1				1														
CA000019-CA013049						1						1							
CA001723-CA001715									1										
CA000019-CA001715									1										
CA001723-CA001718									1										
CA000019-CA001718									1										

Appendix 2 – Linear equation by bridge

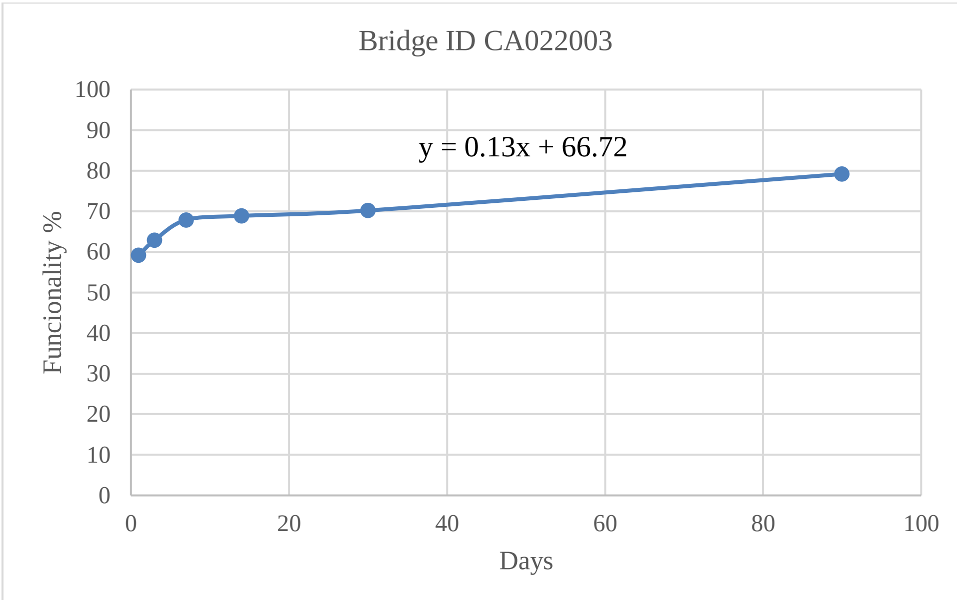


Figure 105. Linear equation for reconstruction time Bridge ID CA022003

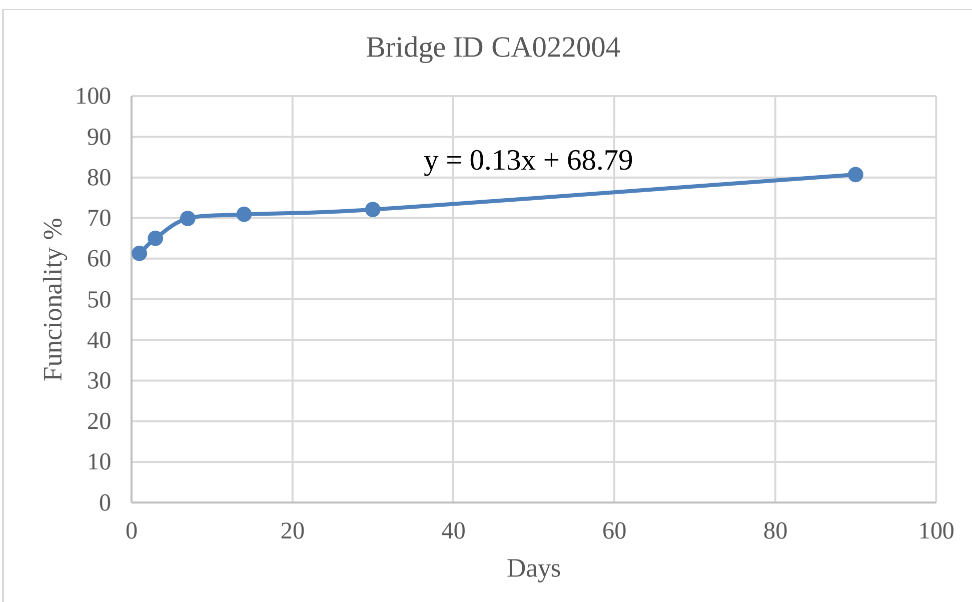


Figure 106. Linear equation for reconstruction time Bridge ID CA022004

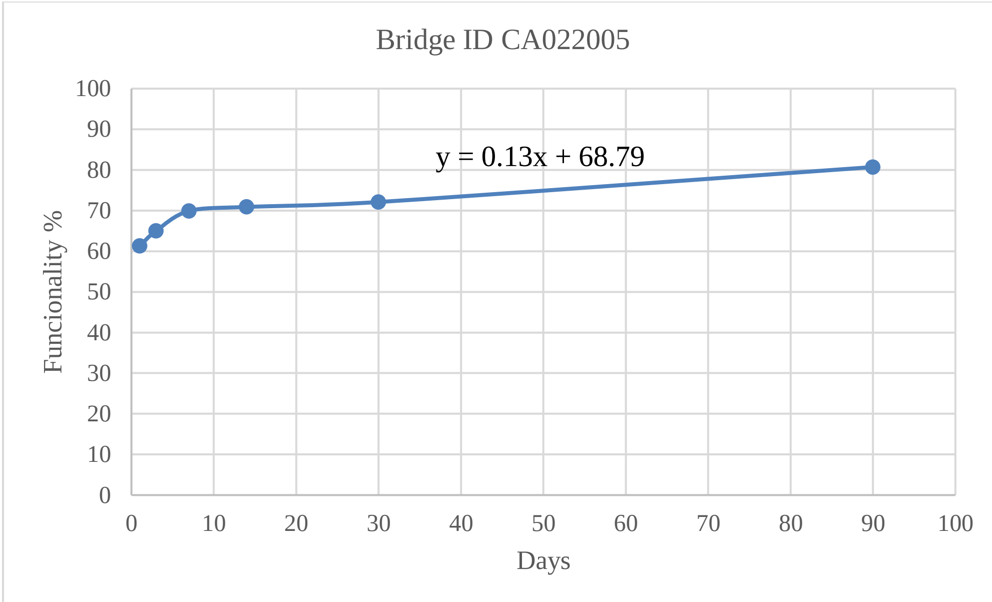


Figure 107. Linear equation for reconstruction time Bridge ID CA022005

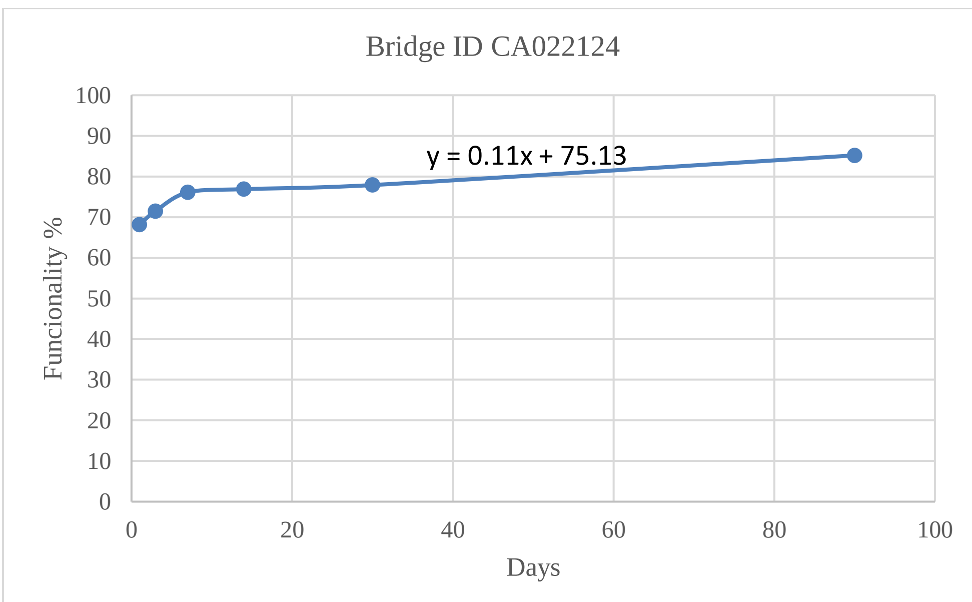


Figure 108. Linear equation for reconstruction time Bridge ID CA022124

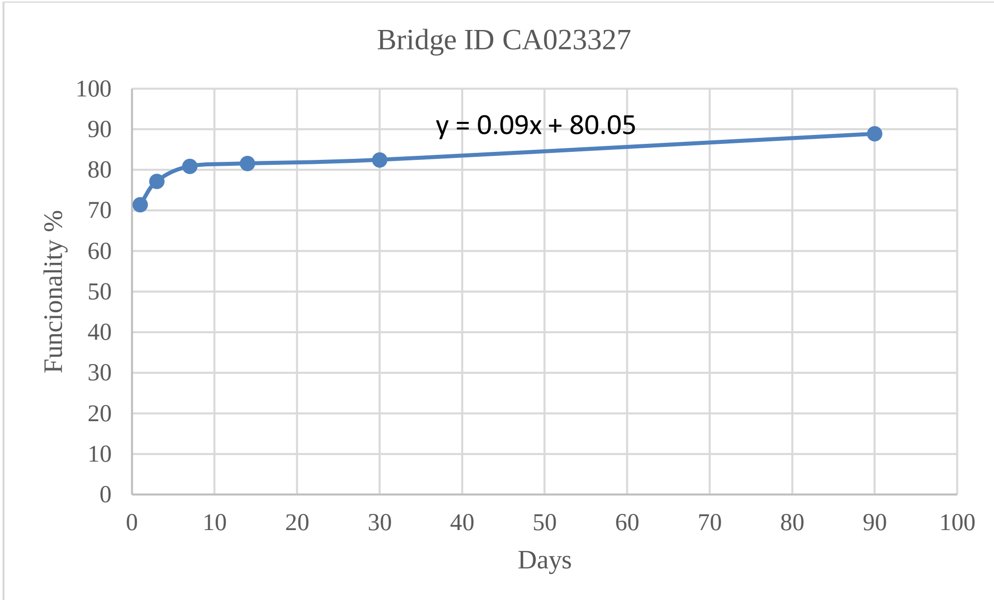


Figure 109. Linear equation for reconstruction time Bridge ID CA023327

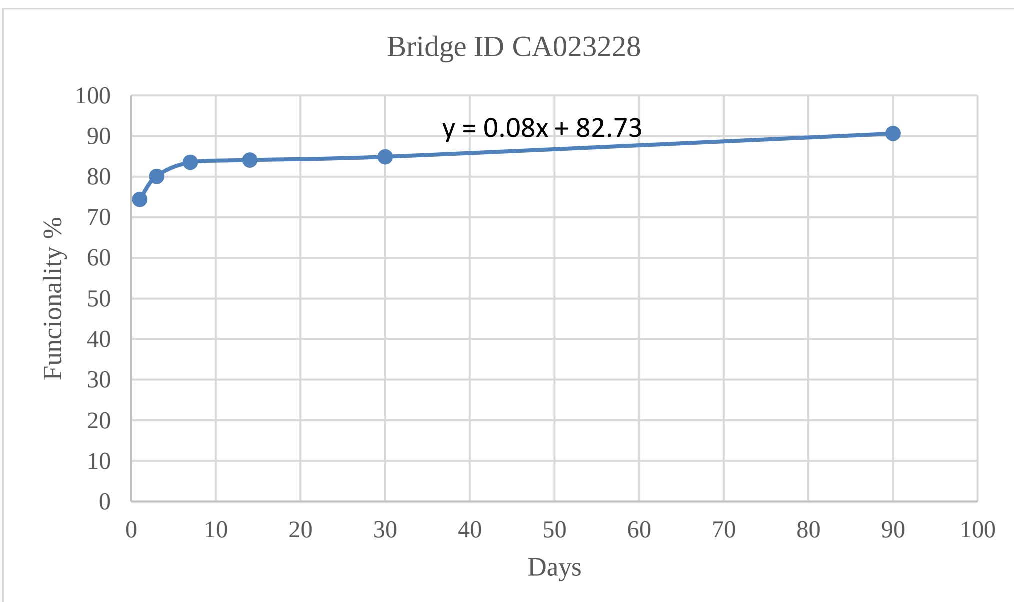


Figure 110. Linear equation for reconstruction time Bridge ID CA023228

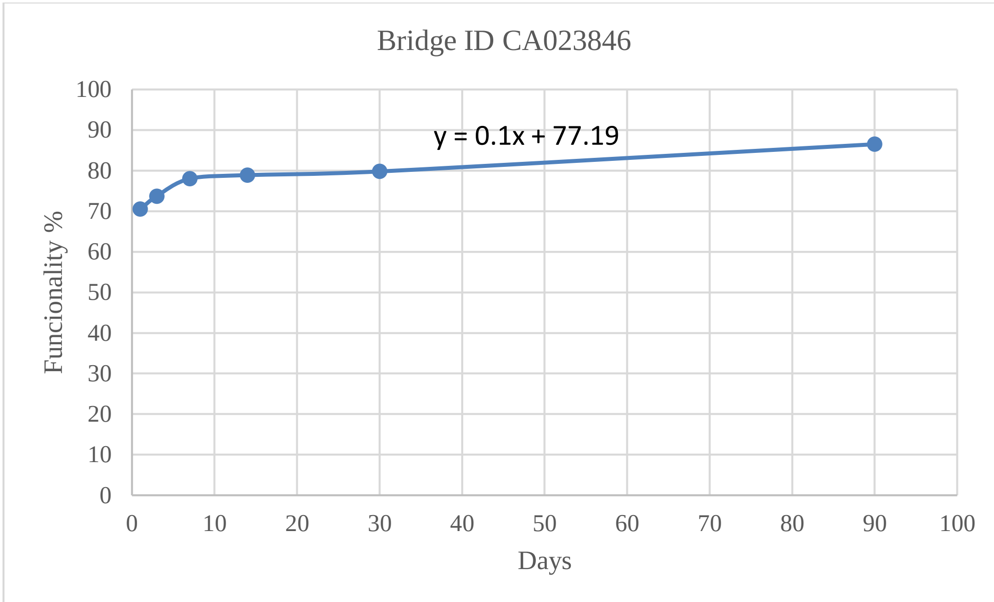


Figure 111. Linear equation for reconstruction time Bridge ID CA023846

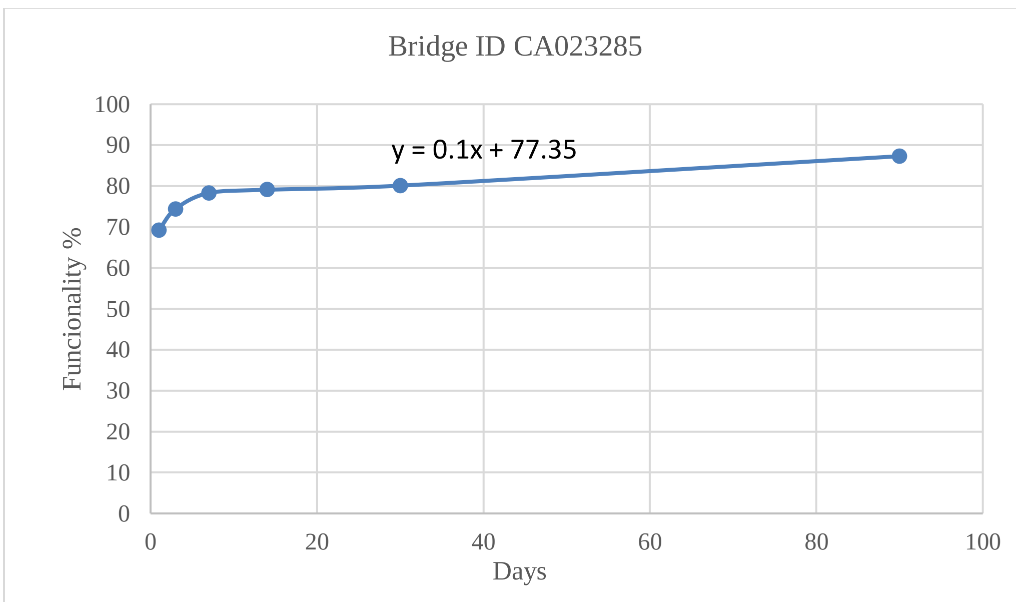


Figure 112. Linear equation for reconstruction time Bridge ID CA023285

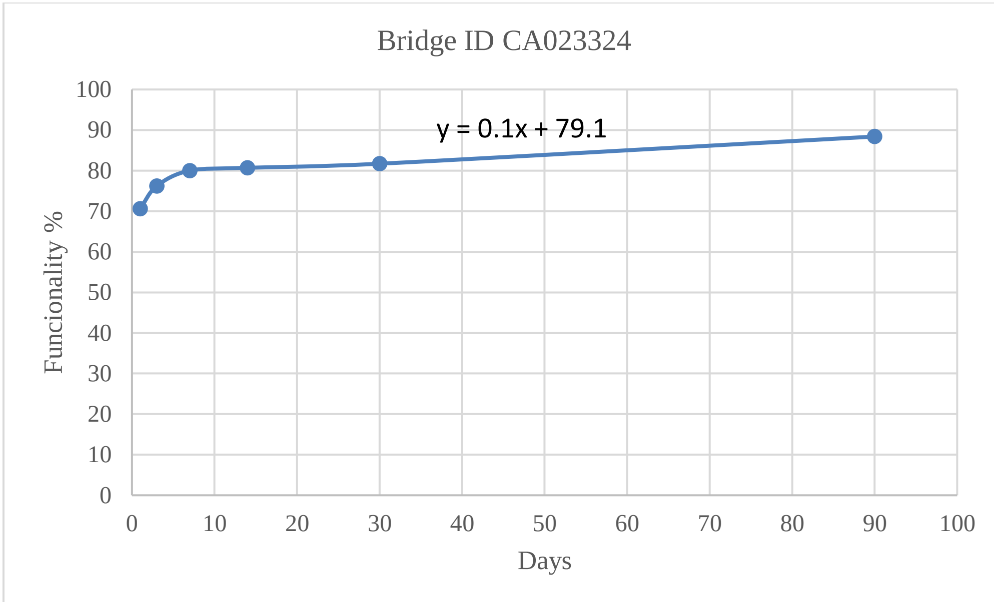


Figure 113. Linear equation for reconstruction time Bridge ID CA023324

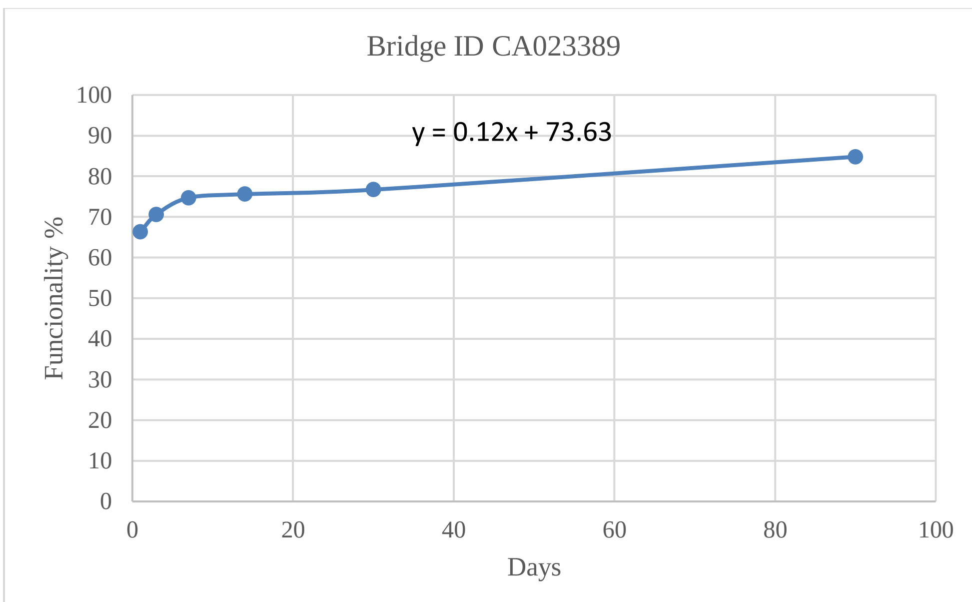


Figure 114. Linear equation for reconstruction time Bridge ID CA023389

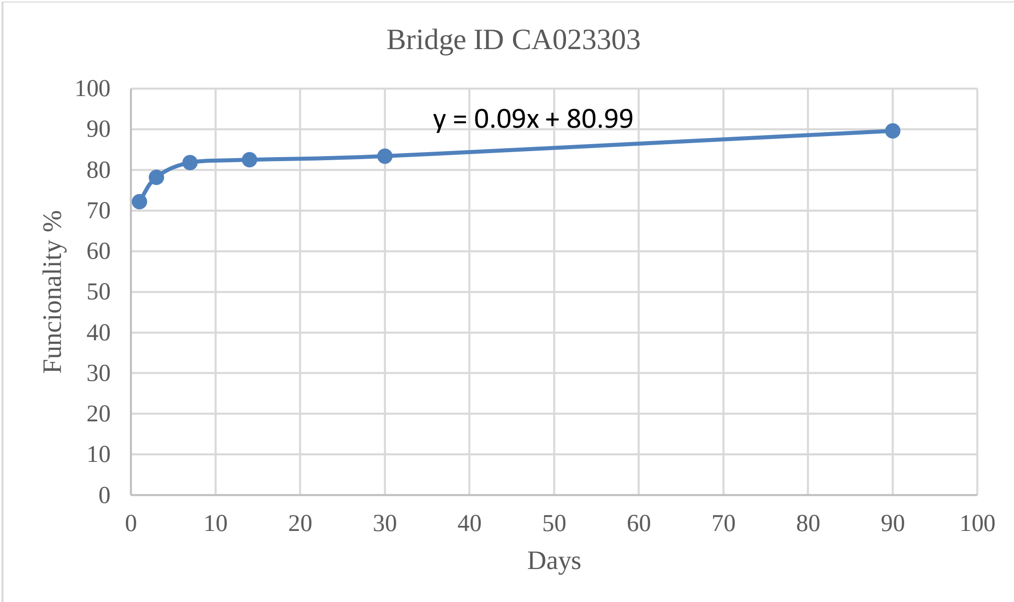


Figure 115. Linear equation for reconstruction time Bridge ID CA023303

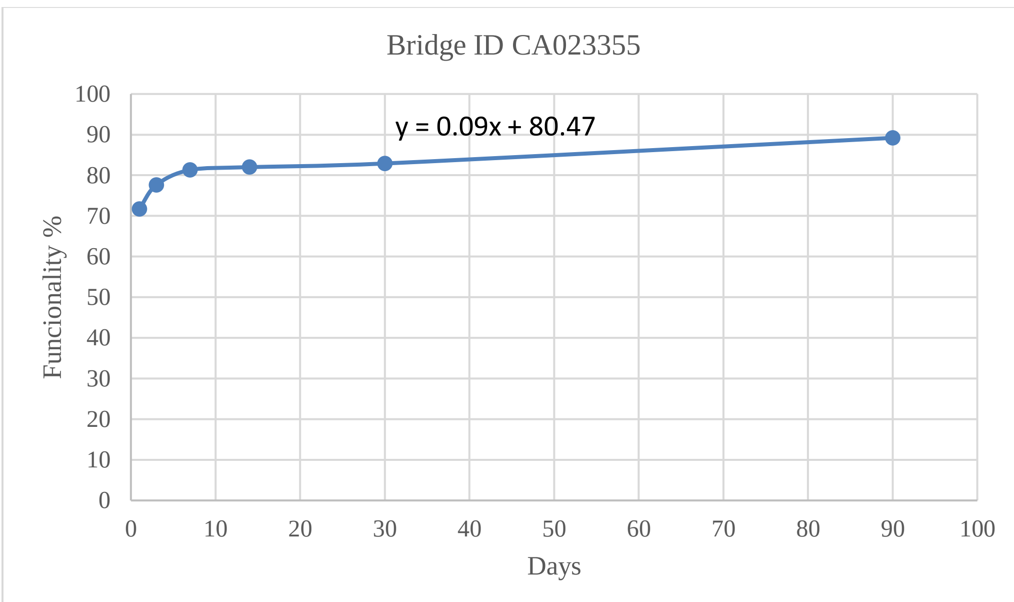


Figure 116. Linear equation for reconstruction time Bridge ID CA023355

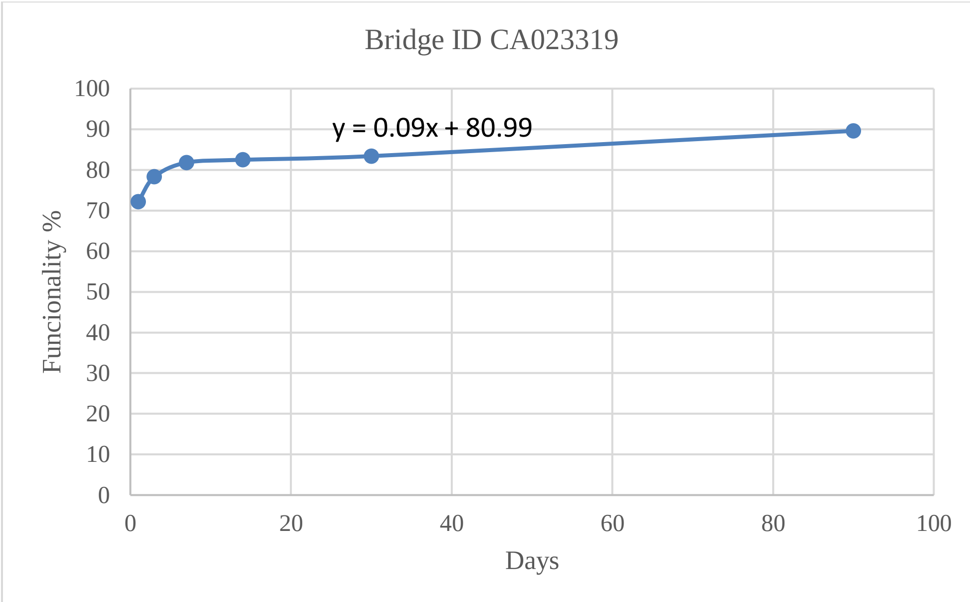


Figure 117. Linear equation for reconstruction time Bridge ID CA023319

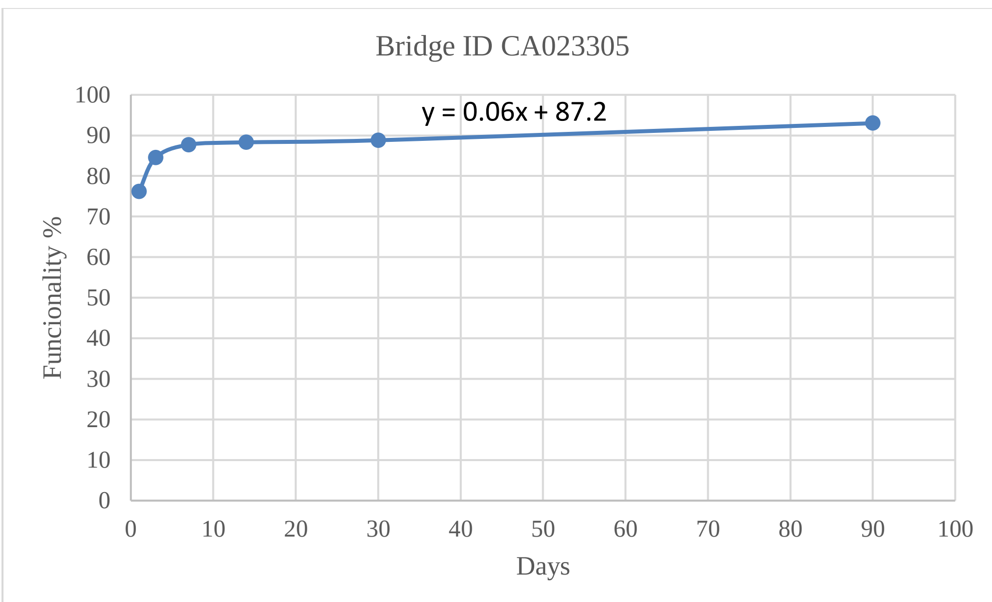


Figure 118. Linear equation for reconstruction time Bridge ID CA023305

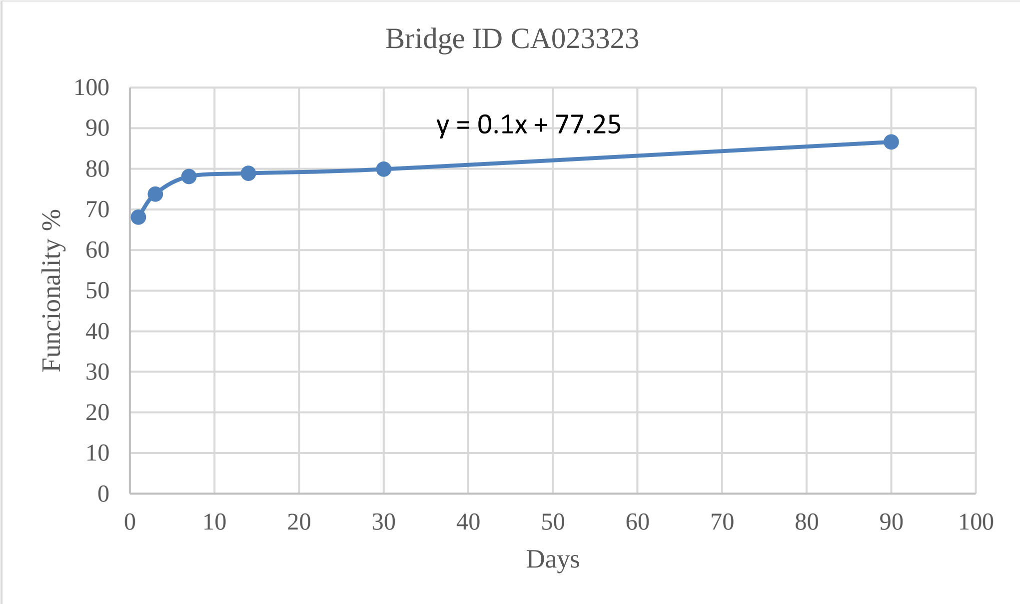


Figure 119. Linear equation for reconstruction time Bridge ID CA023323

VITA

Diana Mercedes Rodriguez Coca

Candidate for the Degree of

Doctor of Philosophy

Thesis: A METHODOLOGY FOR PLANNING RECONSTRUCTION ACTIVITIES AFTER A DISASTER CONSIDERING INTERDEPENDENCIES AND PRIORITIES

Major Field: Industrial Engineering

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Industrial Engineering and Management at Oklahoma State University, Stillwater, Oklahoma, United States in May, 2020.

Completed the requirements for the Master of Science in Industrial Engineering at Universidad de los Andes, Bogota, Colombia in 2006.

Completed the requirements for the Bachelor of Science in Industrial Engineering at Escuela Colombiana de Ingenieria Julio Garavito, Bogota, Colombia in 2000.

Experience:

Diana Rodriguez's research interests are in the areas of optimization, logistics, hazardous waste management, and emergency management. She has worked as a professor at the Escuela Colombiana de Ingenieria Julio Garavito from 2000 to 2019. In addition, she has also worked as a graduate research and teaching assistant in the School of Industrial Engineering and Management at Oklahoma State University from 2011 to 2019.