

Formulating Earthquake Response Models in Iran

by

Michael D. Metzger

Bachelor of Science in Electrical Engineering and Computer Science

Submitted to the department of Electrical Engineering and Computer Science

In Partial Fulfillment of the Requirements for the Degree of

Master of Engineering In Electrical Engineering and Computer Science

at the Massachusetts institute of Technology

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Signature of Author: _____

Department of Electrical Engineering and Computer Science

May 10, 2004

Certified by: _____

Richard Larson

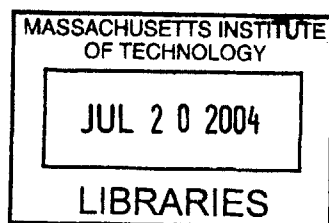
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ABSTRACT

The objective of this paper was to try and find the optimal distribution of rescuers after an earthquake with a very large magnitude caused major damage in two different cities. A model was developed to optimally divide all of the available rescuer workers such that the expected number of lives saved was maximized. When the method was tested on random sets of data on average a 5% improvement in lives saved was found. However it was also determined that there was a positive relationship between percent improvement and severity of the earthquake. This shows that the method is especially effective when extreme amounts of damage occur.

Thesis Supervisor: Richard Larson

Title: Professor of Civil and Environmental Engineering

Section 1: Background and Introduction:

A recent survey conducted by the US department of the Interior determined that earthquakes have resulted in more deaths than any other type of natural disaster. They have cost the world over three trillion dollars and claimed more than two million lives since 1950. Some earthquakes are so strong that they can cause large buildings to collapse, trapping and in many cases, injuring or killing their occupants.

Earthquake survivors rely on the assistance of trained rescue workers such as military personnel, fire fighters, and police officers. It is vital that a nation has a method to organize and deploy rescuers to proper locations in an efficient manner if they are to maximize the number of lives saved. Some countries, including China and Japan, possess sophisticated rescue models as well as entire governmental departments devoted to improving rescue efforts.

However, many nations presently lack sophisticated emergency response models. This can have disastrous effects. On August 17th, 1999, Turkey was struck with an earthquake with magnitude of 7.2 on the Richter scale. Due in part to its lack of an emergency response model, over 20,000 people lost their lives. As a contrasting example, an earthquake of similar magnitude struck China several years prior, but only 3,000 people lost their lives. The Turkish government received a tremendous amount of criticism for its poor rescue effort. There was no procedure for dispatching rescue workers resulting in massive delays amounting to hours and only 117 doctors were dispatched. Eventually, city officials were so frustrated that they relied on British troops in the rescue effort. In the meantime, thousands of trapped people died.

As demonstrated in the prior example, a well planned rescue method is vital to saving lives. One nation that currently lacks a sophisticated model is Iran. While Iran is the most earthquake prone country in the world, it also requires a great deal of improvement to its current method. My advisor, Professor Richard Larson, who traveled

to Iran last year, was contacted by Shireff University in Tehran and was asked to help improve the current rescue efforts. For the past six months, Professor Larson and I have been examining a special optimization problem within the rescue effort and have developed a basic model that on average, improves the number of people rescued by over five percent. The problem involves allocation of rescue workers in the case of severe damage to two cities in order to maximize the lives saved.

Following the introductory sections, the problem is presented formally with a description of the variables. We then explain the structure and details of our model. Finally, results, conclusions and possible extensions are presented.

Section 2: Iran and Earthquakes

The Basics of Earthquakes

Earthquakes are caused by movement in the earth's crust. They occur mainly at locations near fault lines. The damage an earthquake causes is due to the seismic waves that oscillate from the epicenter of the earthquake, causing the ground to shake and damage to occur. Earthquakes are measured on a log magnitude scale known as the Richter scale. An earthquake with magnitude five or less is not considered to cause very much damage, while an earthquake of magnitude six or more can potentially destroy an entire city. The following table describes the Richter scale.

The Richter Scale

Mag.	Effect	Number Per Year
Less 2.0	Micro earthquakes, not felt.	About 8,000 per day
2.0-2.9	Generally not felt, but recorded.	About 1,000 per day
3.0-3.9	Often felt, but rarely causes damage.	49,000 (estimated)
4.0-4.9	Noticeable shaking of indoor items.	6,200 (estimated)
5.0-5.9	Can cause damage to poorly constructed	800
6.0-6.9	Can be destructive up to about 100 miles.	120
7.0-7.9	Can cause serious damage over larger areas.	18
8.0 or greater	Can cause serious damage hundred miles	1

Figure 1: The Richter Scale

Knowing how earthquakes are measured is useful, but knowing where and when they occur is vital in developing an optimal response algorithm. Unfortunately, scientists have yet to develop reliable earthquake prediction tools. They have, however, developed a method to determine the probability of an earthquake occurring in a certain region. The relationship between geographic region and earthquake is known as Seismic Hazard Mapping. The Global Seismic Hazard Assessment Program (GSHAP) was launched in 1992 by the International Lithosphere Program (ILP) with the goal of mapping earthquake hazard for each region of the world. Scientists came up with the following scale to measure ground sensitivity. The scale runs from zero (no hazard) to 5 (Very High Hazard).

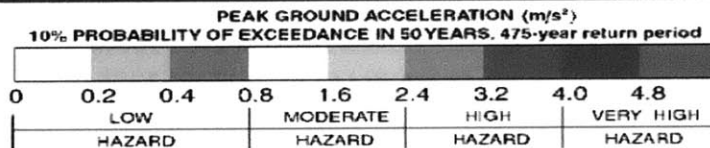


Figure 2: Scale for Seismic Hazard Rates

Using earthquake engineering methods, specifics for which are beyond the scope of this paper, scientists developed a world seismic hazard map. These maps allow nations to determine their vulnerability level to earthquakes and take the necessary measures to develop response allocation methods.

Iran and Earthquakes

Iran is situated in the geographic area between the Middle East, Northern Africa, and South Eastern Europe. The area has served as a passage way from Europe to Asia for centuries. The nation of Iran, however, is also located right on the cusp of the Pacific Rim. It also sits directly above the Persian Gulf and is currently populated by more than 15 million people. While many people recognize this area for its extreme political instability, few realize how vast its geologic instability is.

Iran is currently noted as the country that has experienced the greatest number of major earthquakes in the last century. Unfortunately, it is also one of the least prepared countries due to the lack of education and engineers available. Over 200,000 lives have already been lost in Iran because of earthquakes. Even more startling is that each earthquake costs the nation up to 10 billion dollars in recovery which takes even more away from its struggling economy. A proper emergency response algorithmic method can reduce lives lost by an estimated 5%.

Most earthquakes occur where the southern parts of Asia border the Pacific and Indian Oceans and where the west coast of the America's border the Pacific Ocean. These areas are home to eighty-one percent of the major earthquakes that have occurred. A map of where major earthquakes have occurred is shown below:

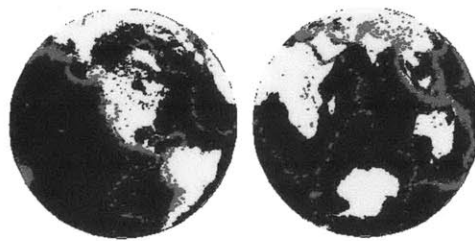


Figure 3: Plot of Major Earthquakes

Structurally, the location of Iran is specifically unstable since it sits between the two major faults of the Eastern Hemisphere. Over ninety- five percent of earthquake deaths have occurred in that region. Over half have been Iranian people. The following chart shows where Iran ranks in terms of number of fatalities due to earthquakes.

Country	Earthquakes
Iran	16
Japan	15
China	13
Turkey	9
India	7

Figure 4: Number of Major Earthquakes By Country

This data has led most scientists to conclude that Iran is the most earthquake prone country in the world. This is mainly due to its unfortunate location on the Pacific Rim. However, in order to evaluate the current Iranian earthquake response model, we must examine the number of deaths caused by earthquakes. The following table shows this data by country.

Country	Deaths
China ¹	1.2 Million
Iran	553,000
India	300,000
Chili	274,000
Japan	51,310

Figure 5: Earthquake Related Deaths By Country

Examining the table above, we can make some very significant inferences. Notice that Japan has experienced nearly the same number of major earthquakes as Iran; but, at the same time, has lost less than one tenth the number lives that Iran has. This initial observation led our research team to believe that something was amiss with the Iran earthquake rescue method. Further evidence for this inference is supported by the two nations' similar seismic hazard profiles. We will now explore the current response methods for allocation in earthquake rescues.

Section 3: Overview of Iran's Current Response Procedure

In 1991 a law was passed in Iran that put the Ministry of the Interior in charge of national disaster response planning. The law was created following a major earthquake near Tehran in which thousands of lives were lost due to inefficient response methods. The method that the department developed was broken down into three phases.

Phase One

In this phase, five top officials meet to determine where the earthquake occurred and what its magnitude was. Based on this information, they then attempt to classify the earthquake by severity. Further delegation of authority is based on the classification control of the response method. The three classifications are:

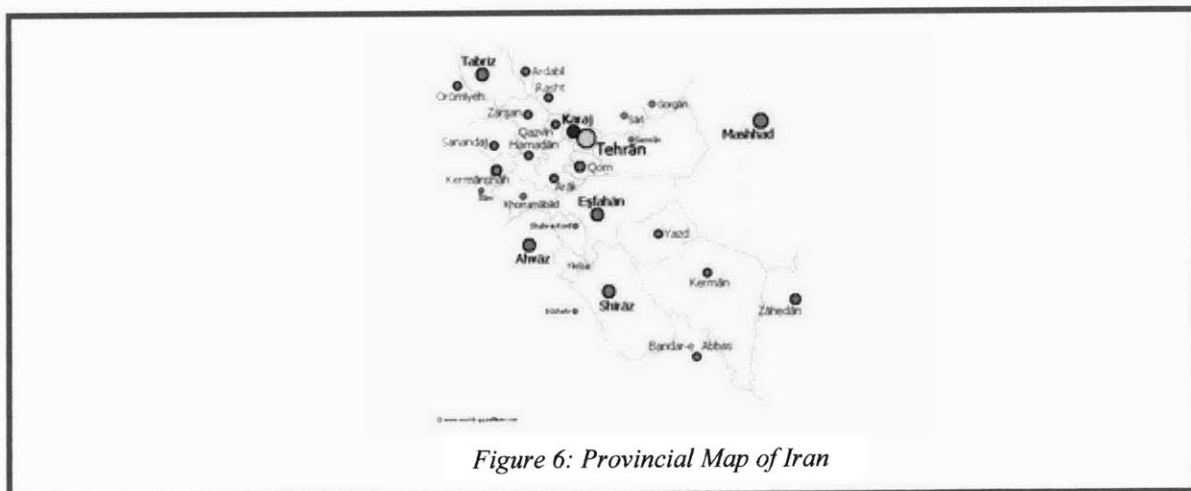
¹ China experienced an earthquake in the 1500's that killed over 700,000 people.

- National: Ministry of the Interior remains in charge for the first seventy two hours
- Regional: Province Governor is in charge
- Local: Local Governor is in charge

In order to classify an earthquake into one of these three categories, a unanimous vote is required. Thus, often lengthy debates occur, while people are trapped under buildings, desperately requiring medical attention.

Phase Two

During this phase, rescue workers are sent to the affected cities based on a few simple principles. In Iran, every province has an adjacent province known as its sister province. The sister province is responsible for sending rescue crews to the affected cities when an earthquake occurs. One major problem with this method is that provinces are formed by political influence. These artificial boundaries are not optimal for rescue coverage. As shown on the map below, due to the unusual population distribution, many provinces are so large that different cities within a province are closer to borders of different provinces. This leads to great spatial inefficiency.



Phase Three

Even if a rescue crew is scheduled to be sent, its destination can be unclear in the case of multiple affected cities. Currently, the method for doing this is to send the crew to the closer of the two cities. However, this can lead to problems. Looking at the map below, assume an earthquake strikes between cities four and five. Cities one, two, and three are chosen to send rescuers.

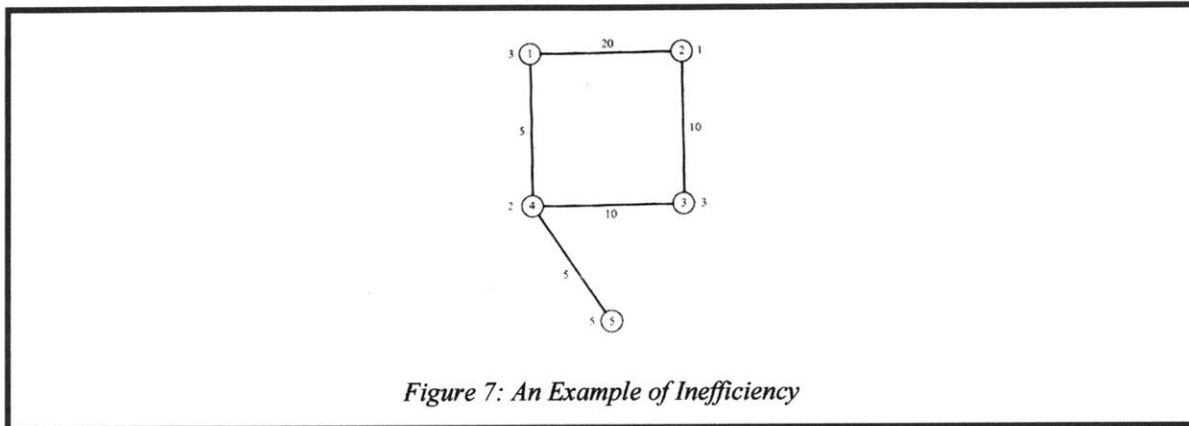


Figure 7: An Example of Inefficiency

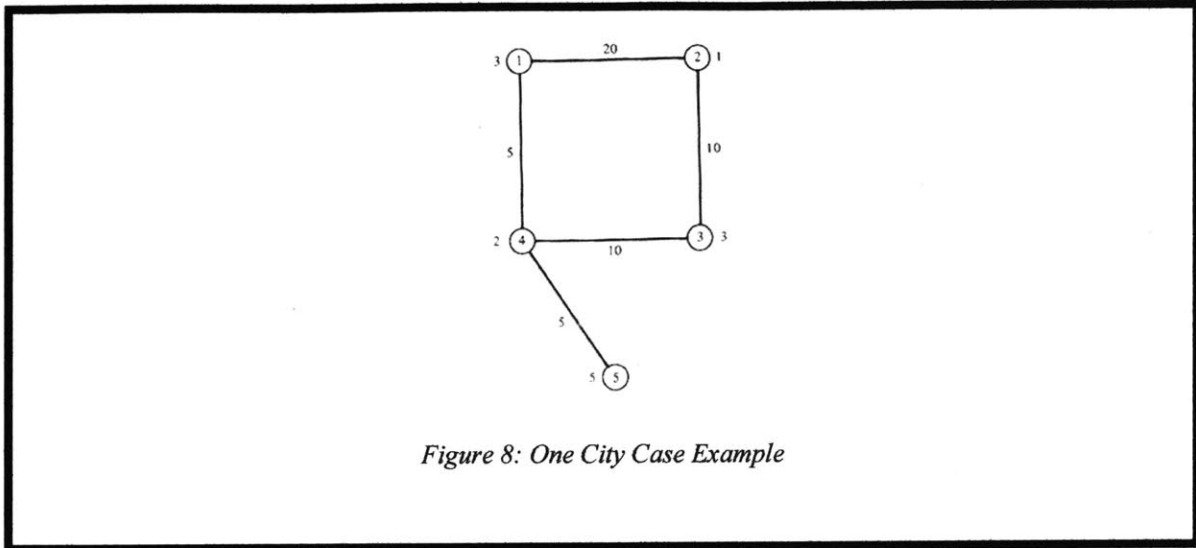
Based on the current response method, all of the rescuers would be sent to city four since it is closer, leaving no one to rescue the trapped people in city five. This results in a major inefficiency. This problem is the focus of our research team's algorithm.

Section 4: The Development of an Optimal Allocation Rescue Model

An introduction and understanding of the various earthquake scenarios is necessary before defining and formulating a mathematical model. This section will introduce the reader to the more general theoretical model. The basic problem is: *Given that an earthquake causes major damage in a city, which cities need to send rescuers in order to maximize the expected number of lives saved?*

The Trivial Once Incident Case

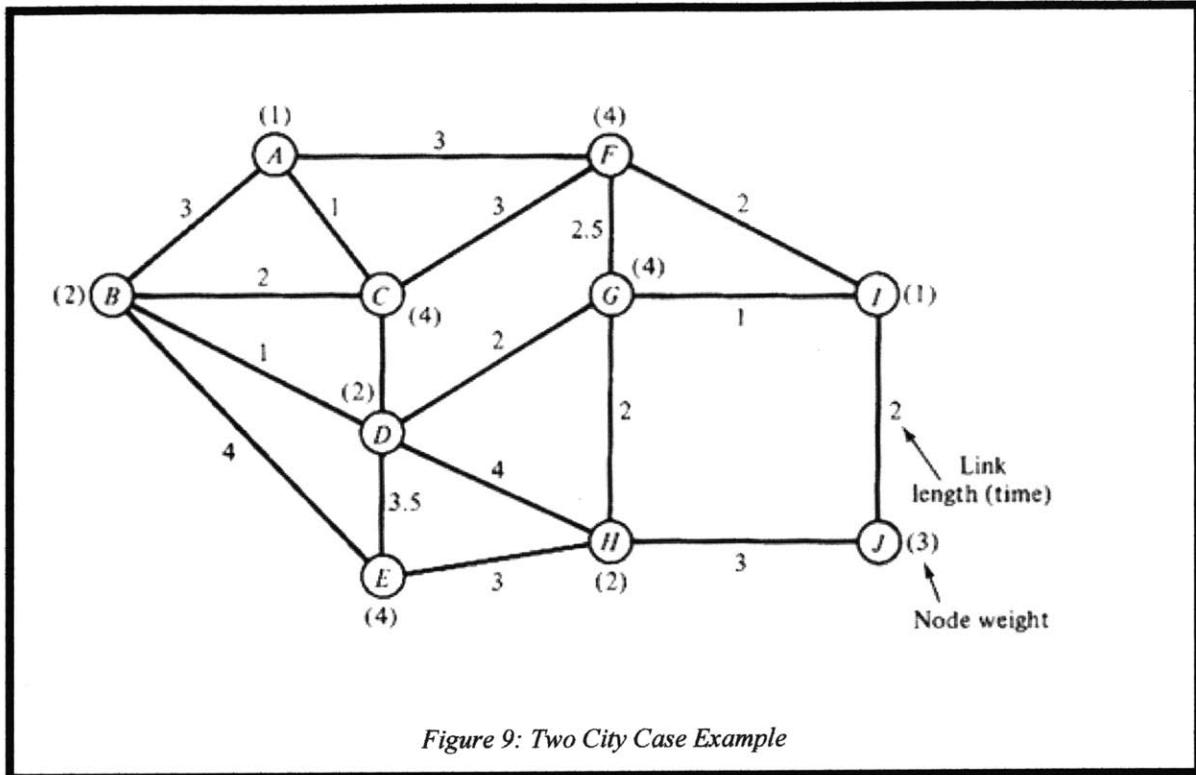
Consider the Network Below:



Assume that a strong earthquake occurs near city 5 and that we want to figure out which rescue crews to send. Since there is only one affected city, the natural choice is to first send the rescuers located closest to city five and then to send the rescuers located in the second closest city and so on. The total number of rescuers required will be determined by the city population as well as the earthquake's magnitude.

The Two City Case

Consider the possibility that a very strong earthquake hits and affects two cities in a significant manner. We now have the problem of two cities requiring crews in order to rescue people. We have a limited number of crews; thus, the problem is to find the optimal allocation of each crew in order to maximize the expected number of lives saved, based on the characteristics of the functions that we defined. Consider the graph shown below:



Consider what happens if an earthquake occurs between cities A and C. Based on the graph, almost every city is closer to C than A. However, after a certain point, crews would be more effective going farther to city A, since the marginal value of additional workers at C is less than their potential value at A. Perhaps half of the rescue crews in city B should go to C, while the rest go to A. Based on damage specifications, recovery rates, travel times and marginal effectiveness rates, we need to find the optimal allocation or division of crews that will maximize the expected number of lives saved. The following section describes the failures in two real cases, when an earthquake caused major damage in two cities and an effective allocation procedure was not in place.

Two Instances of the Two City Case

One of the largest earthquakes of this century took place in Japan in the fall of 1923. On September 1st 1923, an earthquake of magnitude 8.19 struck between Tokyo and its 17 mile southern neighbor, Yokohama. This was the largest earthquake ever to strike the region. Due to the lack of technology available at the time, many thought the earthquake only affected Tokyo, since its epicenter was closer to Tokyo. As a result, after a period of confusion, most rescue crews were sent to Tokyo and not to Yokohama. One reason for this was due to the lack of communication. Since Yokohama was a much smaller and less technologically equipped city, many did not realize the damage that occurred in the city. Thus, as a result of this inefficient distribution, 66,000 people died in Tokyo and 33,000 people died in Yokohama. While Yokohama did have fewer deaths due to differences in population, a much higher fraction of the population of Yokohama died due to the non-optimal allocation of rescue workers. The map below shows the close proximity of the cities.



Figure 10: Map of Japan

Another major earthquake struck Japan in 1995. This earthquake was titled “The Hanshin” meaning great earthquake. The earthquake was of magnitude 6.9 and struck on January 17th 1995. While this earthquake was not as strong and only caused 5,000 deaths, we can learn from the apparent mistakes that were made during the rescue process. The first major error was that the region had never experienced a large earthquake and this earthquake affected two cities: Kobe and Nishinomiya. Thus because of their lack of encounters in the past, the region did not have a rescue method in place for a major earthquake. One of the problems in the country as a whole was that Japan had invested so much money in attempting to predict earthquakes that little had been invested in actual response methods. The government was widely criticized for being unable to assess the damage in either of the cities. Much time was wasted consulting experts to determine the expected damage throughout the region. One journalist quoted in the Japan Times a week after the earthquake hit stated, “‘The Hanshin’ has forced all Japanese to recognize that this country does not have a reliable crisis management system.” Another factor was that the response procedures called for the creation of a council of the affected cities directly after the quake occurred. Since many cities were involved in this quake, the procedure took longer than expected. As a result of not being able to predict damages, an accurate allocation of rescue workers was not determined and the allocation took an abnormally long time. As a result 4484 people in Kobe and 1107 in Nishinomiya died. Some feel that an insufficient number of rescue workers were sent to Kobe.

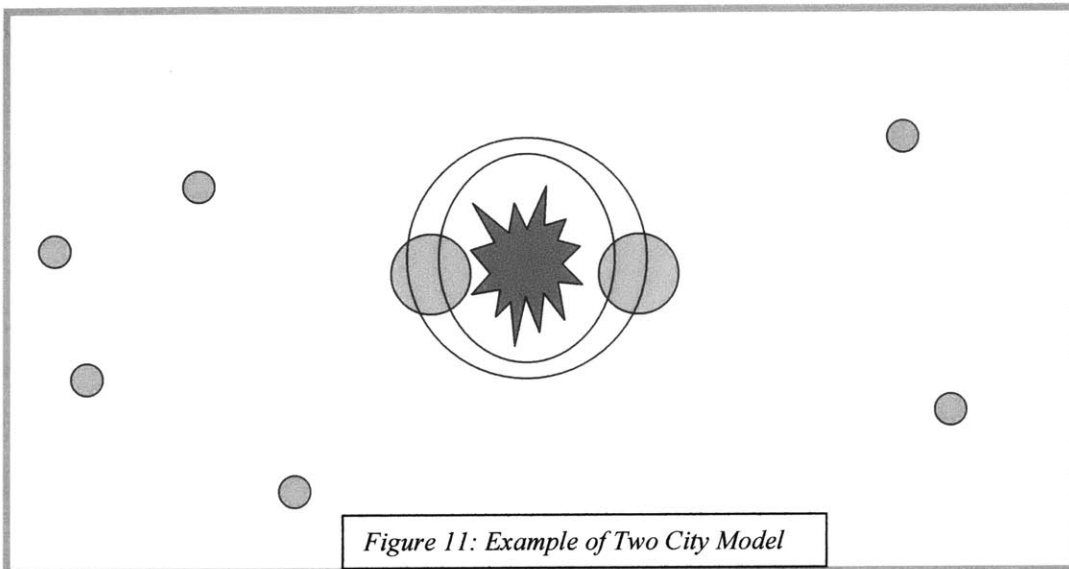
These two examples indicate the need for a two city allocation method that can be implemented when a large earthquake strikes. The following sections of this thesis explain the development and results of the model that we created.

Section 5: The Formal Definition of the Maximization Problem

Definition

The goal was to find an algorithm to compute the optimal rescue allocation given the occurrence of a severe earthquake resulting in damage to two cities. The formal definition of our problem is:

Given: *If an earthquake occurs and causes damage in TWO cities, what is the optimal distribution of rescue workers in order to maximize the expected number of lives saved?*



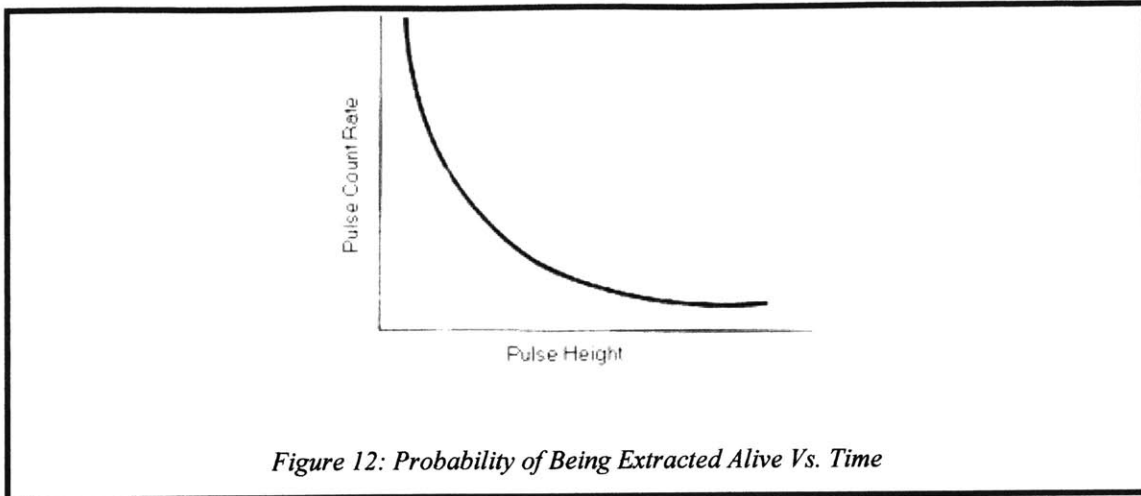
We needed to determine a method to efficiently divide all of the rescuers in cities that were not affected by the earthquake in order to maximize the expected number of lives saved. The method in which this formulation was determined involved many complex mathematical methods. Some of the methods used were: Nonlinear Optimization, Quadratic Interpolation, and Dynamic Maximization. The details of these methods are beyond the scope of this report. We will explain the different factors that affect allocation as well as their effect on distribution. The variables that affect allocation are listed below:

- Time
- Distance
- Magnitude
- Population
- Rescuers
- Building Strength
- Weather
- Returns to Scale

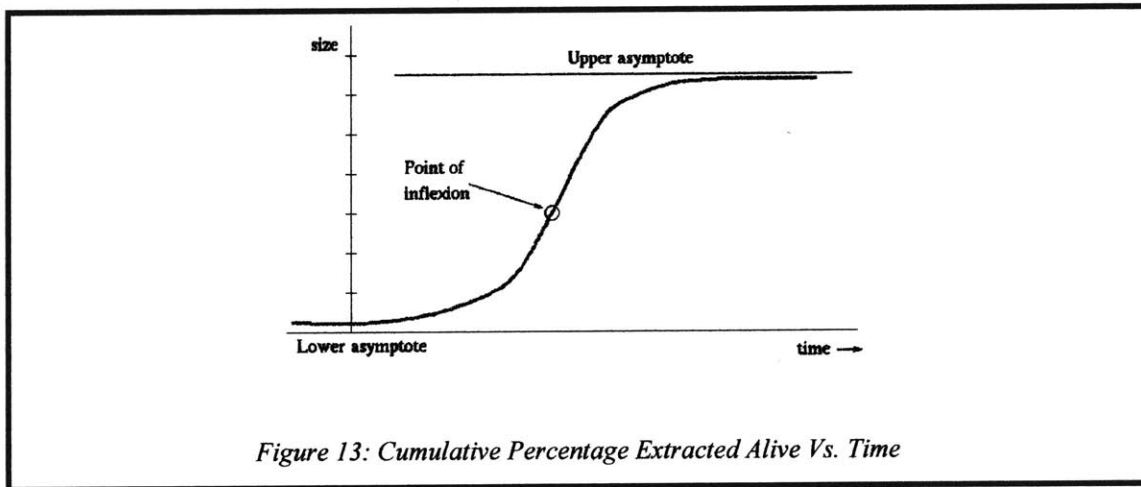
We will now look at each of these variables and describe how they affect the allocation problem.

Time

Time is undoubtedly the most important variable when determining allocation. Performing an earthquake rescue mission is a race against the clock. Every second is vital in rescuing trapped individuals. As time passes, fewer and fewer trapped victims are likely to be rescued alive. A rule developed by earthquake engineers in China known as the “Golden 24 Hours” states that the probability that a trapped victim is rescued alive drops exponentially from .93 to .53 in the first twenty four hours. Thus, it is imperative to expedite allocation in order to maximize the number of trapped victims rescued during this time period. The rule is displayed below in graphical form. The graph shows the probability of a trapped victim being extracted alive versus time.



There is another curve known as the s curve that is used in disaster recovery. This curve plots the number of rescued individuals vs. time. It typically follows an s shape, since initially, it takes organization time before crews can efficiently rescue people, then as time passes, fewer and fewer trapped people are extracted alive. This is shown below.



The following data comes from a recent symposium on earthquake rescue in China. Initially, after an earthquake strikes, on average (based on 4 Case Studies) about 7% of trapped victims are already dead. If a person is extracted during the initial 24 hour period, then they have an 80% survival rate. Between the initial time of an earthquake and the 24 hour mark, no one to date has constructed a continuous curve for this distribution mainly because of the chaos of trying to rescue victims. All of this information is put together post-quake and reconstructed. Sometimes data is even

compiled per twelve hour period or once a day. Specifically, the following data are known:

- 7% of all trapped victims die immediately after a building collapses on average
- On average, rescues focus on rescuing bodies alive as opposed to deceased ones. This is expected and justified since their objective is to save the most lives not extract bodies at the fastest rate. Past reports that show high percentages of alive vs. total victims extracted after the early hours of an earthquake are inflated due to the bias of rescuing living bodies. It is difficult, however, to estimate what this bias is on average and for the purposes of this thesis it is neither practical nor necessary to complete such an analysis. A rough estimation of this bias was taken into account when formulating the curve; it would take a thesis on its own to really get a sense of this bias.
- No continuous data curve exists that plots percentage of live saved vs. time in a continuous domain. The reason for this is during the initial hours continuous tallies are not possible as rescue crews are spread out nor are they practical since the objective is to save lives.
- We know that the cumulative probability of being alive given that one is extracted during the first 24 hours is 80%; however, this is not the same as the probability of being extracted after exactly 24 hours have passed. This number is much lower, around 50%.
- We know, based on case studies, that the probability that a person will be extracted alive, given that he is not extracted during the first 24 hours, is 30%.
- For the third 24 hours, the extraction rate is 5%

Thus, linear interpolation was used to define the curve, given that the shape was a negative exponential. It is virtually impossible to find the exact nonlinear multiplicative function that dictates the bias over time. Thus, we will use the data we have to estimate a bias at two points, thus plotting two points and finding the negative exponential curve that contains them. The data we know:

- At time $t=0$ there is a 93% probability an extracted victim is alive (we will ignore the bias at this point)
- If a victim is rescued within 24 hours, then there is an 80% (with bias) chance that the victim is found alive.

Since the function is a decreasing exponential with a bias that the probability a victim is extracted alive at 24 hours is much less than 80%. Based on the bias and the function type, we will use the two day cumulative expected extraction probability as an approximation for the probability of being extracted alive at 24 hours. Although we know the average value of the function would be right of that in time based on the shape of the curve, we also know that there is a biasing factor that shifts it leftward. Thus, we will assume for the purposes of this paper that the midpoint in time is equivalent to the two day cumulative expected probability which is 50%.

Thus, our two data points are:

$$(t=0, P(0) = .93)$$

$$(t=1, P(1) = .5)$$

We know that the shape of the curve is as follows:

$$P(t) = be^{-at}$$

$$\Rightarrow P(0) = be^{-a \cdot 0} = b = .93$$

$$\Rightarrow P(1) = 0.93e^{-a} = .5$$

$$\Rightarrow \ln(.5/.93) = -a$$

$$\Rightarrow a = .620756$$

$$\Rightarrow P(t) = .93e^{-.620756t}$$

Through further research, post earthquake interviews, and perhaps preplanning, data can be more effectively gathered at future earthquakes to better approximate this curve.

to travel on a straight road than a curvy one. However, if an implementation was created, then these parameters could be easily altered to increase accuracy for the purposes of implementation.

The final issue that needs to be mentioned is when we talk about formulating the model, one key piece of information is the distance a city is from the epicenter. Thus this space is different because an earthquake can hit any point within the country. Rather than trying to estimate distance by using the nearest city as a parameter, it was decided that an additional function would be implemented that calculates the land route distance between any two points given their latitude and longitude. This will be explored later.

Magnitude

Of the two affected cities, one will often be hit with a higher magnitude shock than the other. The higher the magnitude shocks, the more damage occurs in the city (given all else is equal) and thus we can expect more victims to be trapped. We need a function to estimate the damage level or the number of trapped individuals based on the location and magnitude of the epicenter of an earthquake, along with the city's population and profile. The primary task is to find a relationship between magnitude and the distance a city is from the epicenter of an earthquake. Based on this distance, we can predict the magnitude felt by the city, based on the magnitude experienced at the epicenter. Therefore, we need a way to determine this magnitude.

When determining allocation, it is necessary to compare the magnitudes at the two affected cities in order to determine how to allocate rescuers. Earthquake engineers created software in the 1980's in order to determine the expected magnitude felt at a city given the location of the epicenter. Their method created what are known as isoseismic maps. This type of map plots the shaking felt as a continuous spatial function from the epicenter. An example of one of these maps is shown below. These maps radially show the decreasing magnitude gradient from the epicenter. It is important to note that the

magnitude decreases in an exponential manner as one moves away from the epicenter. An example of one of these maps is shown below.

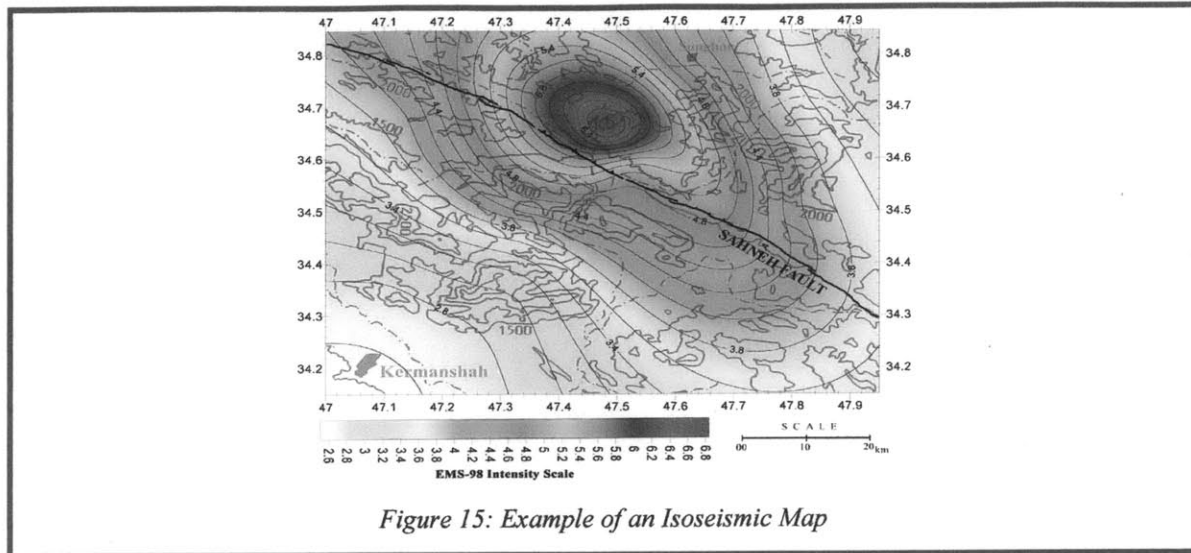


Figure 15: Example of an Isoseismic Map

Based on past evidence, while the intensity function is never perfectly radial, it generally forms some kind of radial-like shape. Thus, when predicting earthquakes, many assume a radial damage pattern for a general approximation method. The only way to do better is to explore the geographic features of the region in depth (mountains, faults, waterways ECT.). While this does increase accuracy, the areas where potential damage will occur are rather close to the epicenter, thus allowing us to assume a roughly circular formation base shown on the map above when predicting damage patterns. Isoseismic maps are a very powerful tool that we can use to estimate the damage that occurs miles away from the epicenter. From this map we can again see the radial pattern. A general rule of thumb we found in our research was:

- Less than 50 kilometers away, roughly same degree of intensity
- Between 50 and 100 kilometers from epicenter, one degree less intensity
- More than 100 kilometers, two degrees less of intensity(aka not really affected)

Population

The effect population has on allocation is similar to the effect that magnitude has on allocation. As population increases, the expected number of trapped victims increases proportionally. The higher the population, the more rescuers needed at the site. This rule will play a role during the algorithm formulation.

One major simplification is that we are only using the 50 most populated cities. We need to consider what the cut-off point should be in terms of population for putting a city into our model. We are also not considering possible gender issues in rescue that may be relevant when using Iran as an example. In Iran, there are very strict limitations to male/female interactions and it is not clear if these distinctions would play a role in our model. Finally, we are not taking into account age distribution in terms of rescue profile. Again for practical purposes, if one wanted to alter these parameters, it would be very easy to do so.

Building Strength

Different cities have different building codes. For example, Tehran the capital of Iran has very strict building codes and visitors to this city would see structures similar to ones they would see in New York. However, in smaller cities like Qom, the buildings are mostly built out of mud or rotted wood and are obviously much less resistant to earthquakes. One of the main influences of building codes is the wealth of the city. When looking at Iran, most of the country struggles economically. Tehran is by far the most prosperous city and thus has much stricter building codes since they can afford to enforce them. Therefore, when determining the amount of expected damage in a city hit by an earthquake, it is not enough just to determine the magnitude. This factor must be combined with the strength of the buildings in the city in order to determine the affected damage. Buildings in more metropolitan cities can resist a higher magnitude of shaking before damage occurs.

When determining the amount of damage in a city after knowing the magnitude felt at that city, we need to take into account the relative building strength of the city in

order to estimate the number of people trapped due to the earthquake. The building strength factor would be used mainly for Tehran. The reason for this is that Tehran buildings are much stronger than the rest of Iran, thus they can withstand more ground shaking than the other cities. To what extent this reweighs the nodes is questionable. It is clear the factor is multiplicative because it reduces vulnerability by a certain percentage. For the purposes of this illustrative model, we will allow for an estimated factor of .8 for Tehran due to their modern structure and a factor of 1.0 for the rest of the cities in the model. If one, however, had the ability and knowledge of earthquake engineering, along with the building codes of each city, these factors could be included to reflect the building materials used in each city.

$$FactorForBuildingStrength = \begin{cases} 0.80 & \text{if Tehran} \\ 1.00 & \text{Else} \end{cases}$$

Rescuers

Before determining how to optimally allocate rescue workers, it is first necessary to determine how many rescue workers are available. In order to do this, we need to create a formulation primarily based on the population of a city that determines the number of qualified rescue personnel in a given city. While it is worth noting in actuality, that the number of rescuer workers in a city is based on many factors, not limited to, but including: population, geographic location, wealth, weather, age distribution, diversity, and educational levels. In order to determine the number of rescuers, however, we need to consider the following:

- We assume that military personnel are trained rescuers, thus, we need to determine the number of military or ex-military personnel that are based in each city.
- We assume that there is a constant proportion of each city's personnel that can assist (aka, firemen, policemen, construction workers ECT.).
- We assume we have a set budget and with this budget we can train X number of rescue workers, evenly distributed throughout the cities.

One major problem with this assumption is gathering the data. This is virtually impossible and an approximation needs to be made. Also, when using the constant proportion of trainees in each city, it should be noted that it will cost more to train people who are more spread out as opposed to people that are located within a closer geographic distance to each other (aka, travel costs, economies of scale). In order to even estimate this proportion, we need a budget and the cost of training an individual.

For the purposes of this model, however, it is beyond our capacity to analyze each of these factors, (some which are quite minor) in order to determine the number of rescue personnel in a given city. For our intentions, we will limit the number of rescuers to be directly correlated to the population of a city. Since population is by far the main factor in determining the number of rescuers this simplification should not grossly over exaggerate our model.

For the purposes of this paper, it is necessary to make an approximation of this constant percentage. By this we mean a constant percentage of the population will be considered to be trained for rescue. We will make the approximation that ½ of 1 percent of each cities' population is trained to perform rescues. With an actual budget, training, costs and qualitative research (such as how many military personnel live in the city, also police and firemen) a stronger relationship can be found. Thus:

$$\text{RescuersInCity} = \text{CityPopulation} * 0.005$$

The next consideration that we took into account was how many rescuer workers would be available to help rescue in an affected city. Thus giving the magnitude of an earthquake in a city we need to determine a function that yields to us the expected proportion of rescue workers that are still able to rescue. This number will obviously be less since many will be trapped or occupied with personal matters. This factor will also be dependant on the magnitude of the earthquake and the building strength factor.

It is clear as the magnitude of the earthquake increases, the number of available rescue personnel will decrease. Again, we have to make another approximation on the shape of the curve. The question is what shape does this curve take? Mechanical engineering logically tells us that up to a certain point buildings will not be affected, then they will start to be affected more and more at a faster rate, until all buildings have collapsed. Therefore, we will use an exponential shape to approximate this function. We know from data on the USGS website that rarely are people trapped within an earthquake of magnitude 4 or less. Virtually every building will be collapsed for an earthquake of magnitude 8. Thus, we will use the following two points to find the shape of our negative exponential curve. Note in the points below, we use .98 to represent almost no rescue worker affected by the earthquake and .01 to reflect almost every rescue worker in a city affected by an earthquake. Thus, we use the same interpolation method as before to approximate the function.

$$(m=4, f(m)=.98)$$

$$(m=8, f(m)=.01)$$

$$f(m) = be^{-a(m-4)}$$

$$\Rightarrow f(4) = be^{-a(4-4)} = b = .98$$

$$\Rightarrow f(8) = 0.98e^{-a(8-4)} = .5$$

$$\Rightarrow \ln(.01/.98) = -4a$$

$$\text{For } 4 \leq m \leq 8$$

$$\Rightarrow a = \frac{4.58497}{4} = 1.14624$$

$$\Rightarrow f(m) = .98e^{-1.14624(m-4)} = .98 * e^{4.58497} * e^{-1.14624m}$$

$$\Rightarrow f(m) = 96.04024e^{-1.14624m}$$

We can now combine this function with the previous one to find the expected number of rescue workers available in the affected cities.

$$RescuersInAffectedCity(m) = CityPopulation * 0.005 * f(m) \quad \text{For } 4 \leq m \leq 8$$

$$R(m) = CityPopulation.48e^{-1.14624m}$$

The final issue that we need to account for when determining the number of rescuers workers available in an affected city is the building strength of the city. We discussed earlier how Tehran was more earthquake resistant due to their strong building codes, thus it is important we add a multiplicative factor of the same percentage to reflect the additional number of workers who will not be affected by the earthquake due to the strength of the buildings in Tehran. Previously for the cities' neediness function, we used a multiplicative factor of .8(or a 1.25 divisor), to be consistent with our other approximation, we use the inverse, namely a 1.25 multiplicative factor for the additional number of rescue workers in Tehran if Tehran's affected. Thus:

$$R(m) = \begin{cases} CityPopulation * 1.25 * .48e^{-1.14624m} (Tehran) \\ CityPopulation.48e^{-1.14624m} (Else) \end{cases} \quad FOR 4 \leq m \leq 8$$

$$\Rightarrow R(m) = \begin{cases} CityPopulation.6e^{-1.14624m} (Tehran) \\ CityPopulation.48e^{-1.14624m} (Else) \end{cases}$$

Weather Factor

Some consideration must be made in the allocation algorithm for the weather at certain cities. Many case studies document how trapped victims, waiting to be rescued, often freeze in the cold and die due to frostbite. Thus, if a city is experiencing particularly low temperatures, the “golden 24” becomes more like the “golden 12”. When two cities are affected, and one is experiencing significantly lower temperatures, extra rescuers must be allocated to this city due to the decreased amount of time to rescue trapped victims. Some cities are located rather close to each of them but at vastly different altitudes. An example of this situation might take place when one city is located in a valley, while the other is located on the top of a mountain. Thus it is important to introduce a multiplicative weather factor. For the purposes of this illustrative model, we will multiply the result by 1.2 if the average temperature is below 10 degrees Celsius, or

else the multiplicative factor will be 1.00. At the present time, we have no further data to estimate the multiplicative effect of weather conditions on rescue efforts further than this broad approximation. Our present data only allows us to make a broad estimation that cold weather inhibits rescue efforts and can possibly kill those trapped, thus knowing that some positive multiplicative factor is needed.

$$WeatherFactor = \begin{cases} 1.20(IfAverageTemp < 10C^{\circ}) \\ 1.00Else \end{cases}$$

Shown below for reference is a table illustrating the wide range of temperatures in the different cities in Iran.

CLIMATE TEMPERATURE (DATA IN CELSIUS)

City	Average Max.	Average Min.	Absolute Max.	Absolute Min.	Average Temp.
Ahvaz	30.8	19.2	51.0	0.0	25.0
Arak	18.0	5.5	39.5	-30.5	11.8
Bandar-e-Abbas	30.4	21.9	45.0	4.8	26.2
Hamedan	18.2	-0.9	37.0	-29.6	9.6
Isfahan	19.9	13.6	40.0	-8.6	19.8
Kerman	29.8	-0.4	40.4	-14.0	16.1
Mashad	20.6	8.0	41.0	-15.4	14.3
Rasht	25.5	7.4	35.2	-8.2	16.5
Shiraz	26.1	10.4	42.0	-6.2	18.2

Tabriz	16.7	5.7	38.6	-17.6	11.2
Tehran	22.3	12.4	40.4	-10.0	17.3
Urmiya	15.6	4.0	34.6	-16.4	9.8
Zahedan	26.6	10.4	42.6	-9.8	18.5
Zanjan	23.6	-4.2	37.6	-27.6	9.3

Figure 16: Temperature Table For Iran

Economies of Scale

In determining the optimal allocation, we must take into account what happens as more and more rescuers arrive in a given city. From case studies and observations, it has been shown that each additional worker is less effective as the number of workers increases. This observation is a variant of the commonly referenced economic term “economies of scale.” Thus when determining where to send the next rescuer, given all the other variables, we must decide at which city he will be most effective, given the number of workers already at each city. In doing this, we make sure no efficiency is wasted, due to the economies of scale effect. We must also realize that cities with more trapped victims need more rescuers, and thus the economies of scale effect applies at different points based on the number of trapped victims. The function below shows how each rescuer is less and less efficient due to the economies of scale phenomenon:

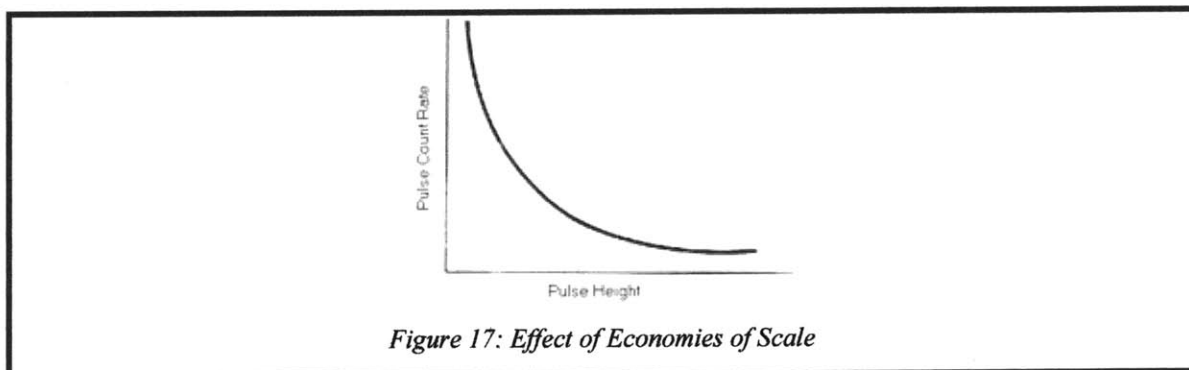


Figure 17: Effect of Economies of Scale

Thus we need a method to quantify this phenomenon. We need to determine how various other factors and variables contribute to the economies of scale effect. We know that the higher the population of the city, the more rescuers will be needed. It is also evident that the higher the earthquake magnitude, the more rescuers will be needed. Thus the economies of scale effect will not occur as early when there is a larger magnitude and or population. We determined through examination of past data that the $n+1$ th rescuer does $1/1000^{\text{th}}$ less work than the n th rescuer. This effect will be further discussed. It is also important to note that this effect does not take place immediately and the point at which it does is determined by the magnitude and population. This negative function, however, will be very important when performing the allocation.

Section 6: The Algorithm

Design of the Algorithm

Using all of the variables along with the methods described above, an algorithm was created to formulate an allocation that maximizes the expected number of lives saved. The algorithm works like a hiker climbing a mountain. It moves rescuers from one city to the other, seeing if the moves improve the expected number of lives saved. If they do, it moves that direction again; if not, it tries another direction until it finds the maximum point, and thus the optimal allocation is based on all of the parameters. The outline of the algorithm is listed below:

- Initially Send All Rescuers From A City To The Closest Affected City
- Then Take 4 Directional Gradients and Shift One Rescuer From One City To the Other.
- Recalculate The Expected Number of Lives Saved
- If Number is Larger, Continue Shifting Until Sum Decreases
- Keep Repeating Until No Movement in Either Direction Improves Result
- Stop

Initialization

The first stage of the algorithm is the initialization stage. This first part of the method is mainly used to gather data and store it in the appropriate locations so it is readily accessible for use when the algorithm is run. First a structure city data was created to store all of the vital characteristics for each city. These characteristics are read in from an outside file and then put into the data structure. The data structure used is an array of class types and each index contains the data on one of the fifty cities. The first piece of data that is read in and stored is the population for each city. Next the latitude and longitude of each city is stored. The secondary characteristics are then read in depending on the situation. These characteristics include the weather factor and the building factor. Once the structure is defined, it is then ready to be used in the algorithm.

The next step is to determine where the earthquake's epicenter is (main focus point). Scientists are able to determine the epicenter of a large magnitude earthquake almost instantaneously these days using modern tools of earthquake engineering. Once the exact latitude and longitude of the earthquake are determined, they are then entered into the program by an outside user. At this point, the algorithmic calculations begin. The first calculation that is needed in order to assess damage is the distance between each city and the epicenter of the earthquake. These fifty distances are calculated using elementary mathematics and are then entered into each of the indices of the data structure. The final piece of data that is entered by the user is the magnitude felt at the epicenter. This magnitude can be calculated separately using a seismograph. Once the magnitude is calculated and entered a few preliminary calculations are performed.

The next phase of the algorithm is used to determine if two cities have severe damage caused by the earthquake, and if they do which two cities are affected. Since we assume a radial damage pattern based on isoseismic maps, we need to perform a search. The algorithm then performs a linear search to determine which two cities are located closest to the epicenter of the earthquake. This is performed in $O(n)$ time. Once these

cities are identified their information then needs to be transferred to another data structure. This data structure is an array of classes, with two indices, called `ecitydata`. The information for the closer of the two cities is written into the first index, the second into the second. The following data fields are copied: name, population, latitude, longitude, strength, and weather. Once this information is complete, the next step is to calculate the expected magnitude at the closer of the two cities. Using the functions defined in the previous section, these magnitudes are calculated. Then, if both of them are not above 5 on the Richter scale, the earthquake is not considered major and the algorithm ends, or else it proceeds onward.

The final step in the data gathering portion of the algorithm is to determine the distances between each of the fifty cities and the two affected cities. It is important to note that these distances are stored in the city data class and are also calculated for the two affected cities (i.e. one component will be zero for each of these). These quantities are determined through elementary methods. Once these calculations are made it is necessary to determine how many rescuers are available in each city. Thus the functions that define these quantities were described in the previous section. The number of rescuers is calculated and stored in the city data type for all fifty cities including the two affected cities using the appropriate formulas depending on whether the city was affected by the earthquake. Once these quantities are determined, it is necessary to formulate the initial allocation.

Initial Allocation

The basis for making the initial allocation is based on a simple principle. That principle is given that a city is less than twenty four hours away from at least one of the affected cities', send all of that city's rescuers to the closer of the two affected cities. It is important to note that the initial allocation method does not take into account magnitude, population, or any of the secondary factors. Using an assignment function, all of the rescuers are allocated to the closer of the two cities. Note: their four other fields in each index, these fields keep track of the rescuers who have been shifted and who have not yet

been shifted. We will explain this issue more later. Once the initial allocations are made, it is then necessary to calculate how long it will take the rescuers to arrive at the affected city. Once the travel time is calculated for every city, then a function is used that takes the travel time and compares the number of rescuers that will be at each city during each hour. These two arrays of 24 indices are stored in the `ecitydata` class. Thus at this point, it is known how many rescuers will be at each of the two affected cities during each hour.

The next step is to formulate how many lives will be saved at each of the affected cities during each hour. The main determinants of how many lives will be saved during an hour are dependant upon the number of rescuers on site each hour, based on the golden twenty four hour rule. Thus a method was formulated based on past data to calculate the expected number of lives saved per person per hour. When computing this value, the economies of scale effect must be taken into account. Because little research is available on the matter, the way we formulated a function was by using variations of sensitivity analysis on past data. We tried to determine how small changes in different factors such as magnitude, population, and number of rescuers affected the expected number of lives saved per person given an hour. However, it is important to note that the function is a weighted decreasing function dependant on the hour. The expected number of lives saved is calculated for both cities each of the twenty-four hours. The result is then summed to find the total expected number of lives saved. This is our initial solution whose value we will try to improve upon using the optimization technique.

Optimization

The optimization procedure is based on basic gradient surface analysis. The objective of the optimization is to see if moving rescuers to the city that they are not closest to will increase the expected number of lives saved. It is clear, if we are moving rescuers to the farther city, that they will have less time to rescue people; however, we want to consider that the other factors often outweigh the extra travel time. The idea behind the problem is that other factors such as differences in magnitude, population and number of rescuers on hand can be such that the extra distance traveled and less time to

rescue still translate into more expected lives saved given the city profile outweighing the cost of longer travel.

The way that this is determined is by calculating a directional gradient. The first derivative is found by moving the closest worker initially assigned to city one and is still at city one to city two. After the move is made, the total number of expected lives is calculated and stored in the same exact manner as above. The other derivative is found in a similar manner. This is found by moving the closest worker at city two that was initially assigned to city two to city one. Then once again, the same calculation is repeated. The three values are then compared, the initial solution, the solution where we moved one worker from city one to city two, and the solution where we moved one worker from city two to city one. If the initial solution results in the highest number of expected lives saved, then that is the final solution and the program aborts with that current allocation. If either of the other two is higher, whichever is highest is the direction we move in. What we mean by this is that we then permanently make the switch and the new solution becomes the new target solution that we are trying to beat.

If the one of the movement resulted in a greater number of expected lives saved then the gradients and movements are then again computed using the previous result as the new solution that we are trying to improve upon. The procedure is run until neither of the two derivatives results in a higher number of expected lives saved. At this point the program terminates. The optimization procedure described above can be thought of as a hiker waking on a surface trying to find the highest point. After each step, the hiker looks and sees the direction of all of the possible next steps, and moves in the step that will increase his altitude by the most. If this is no step that will increase his altitude, he stays where he is and considers himself to be at the highest point. One main assumption is used when arguing the correctness of this algorithm. The main assumption is that the surface is smooth and that there are no local maxima or minima. If this were the case then when the hiker reaches a local maximum, he would stop at that non-optimal point (assume he has very bad eyesight and can't see the higher peak). We can assume this with reasonable confidence since we are looking at a two dimensional problem with

an expected smooth plane based on these properties. If there were more than two cities, then we would be unable to make this assumption.

Section 7: Results

Test Case

The first step was to verify that the algorithm was correctly coded. In order to do this, we created a series of simple test cases. These were designed to comprehensively test all aspects of the code and were composed of a variety of different distributions. We solved these by hand and then ran them in the simulator. An example of one such test case is shown below.

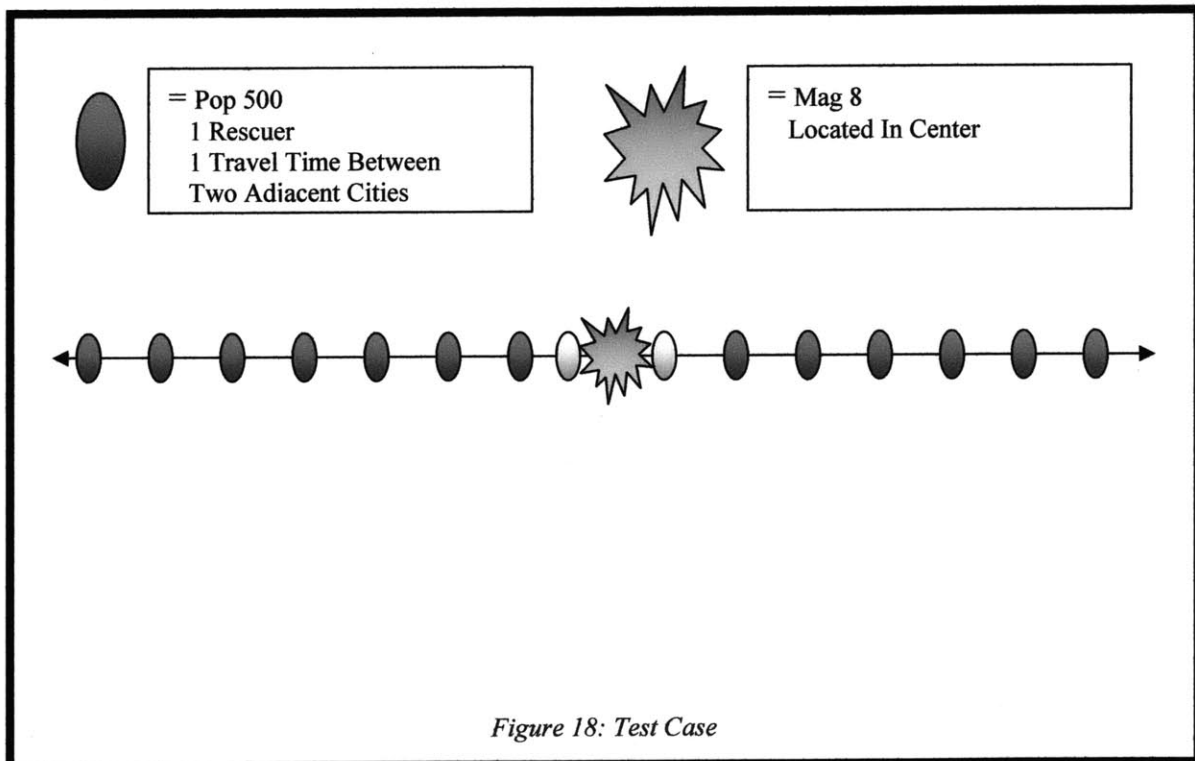


Figure 18: Test Case

In this test case, fifty cities were located on the same longitude. The cities were aligned linearly with equal spacing between them. An earthquake of magnitude eight

was positioned in the center of the line. The travel time between adjacent cities was one hour. For the purposes of the test case, we assumed that all cities had a population of 500 and that each city (regardless of whether or not it was affected) had one available rescuer. Then, to simplify the solution, we defined the number of lives saved each hour as the number of rescuers at the site that hour. Based on these parameters, it was clear that the optimal solution was to send the rescuer of each city to the closer of the two affected cities. Thus, all the cities left of the earthquake sent their rescuer to the city left of the earthquake that was affected, while the opposite would be true for cities on the right. In order to test the correctness of the algorithm for an initial allocation, we sent each rescuer to the FARTHER of the two affected cities. Thus, we started out with the worst possible solution. When we ran the simulation, it correctly transferred each rescuer to the opposite city. Many test cases were run that are not presented here.

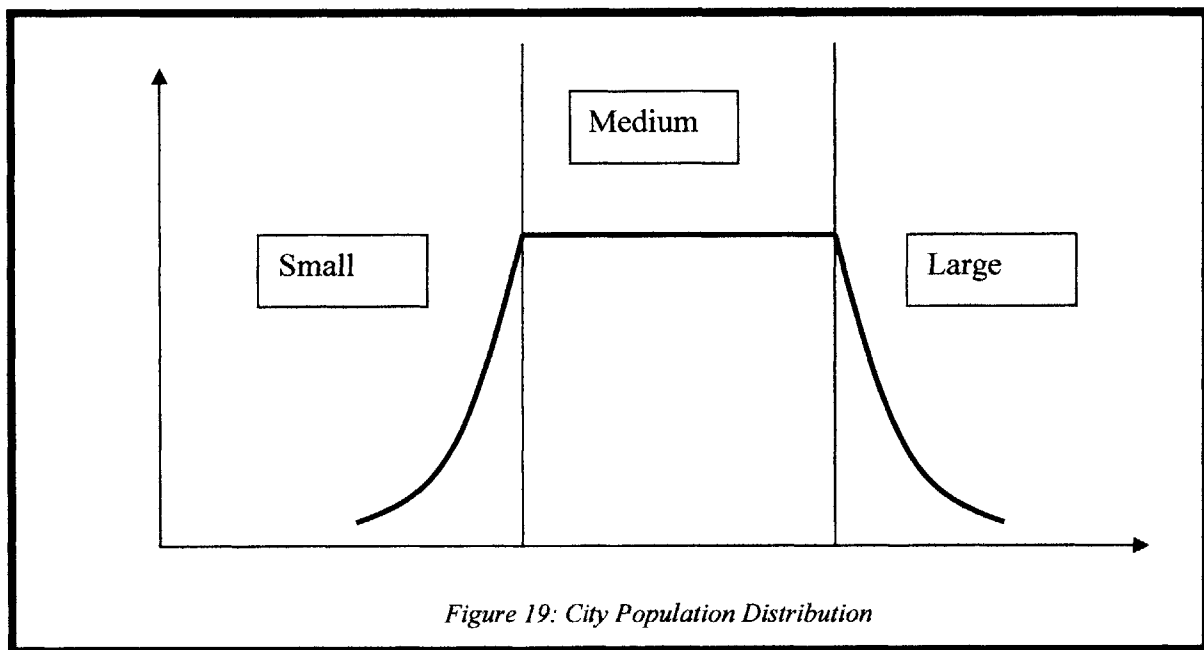
An Example of a Scenario

Since the algorithm is extremely intricate, it was decided to run the code thousands of times on random distributions. The purpose for doing this was to understand the dynamics of how certain factors correlated to certain results so that data could be better interpreted. Random generators were used to generate a large number of different scenarios. A 100 by 100 Kilometer grid was used as a base. Within the grid, we located fifty points, each of which represented a city. The process by which the city size and population was determined involved three steps:

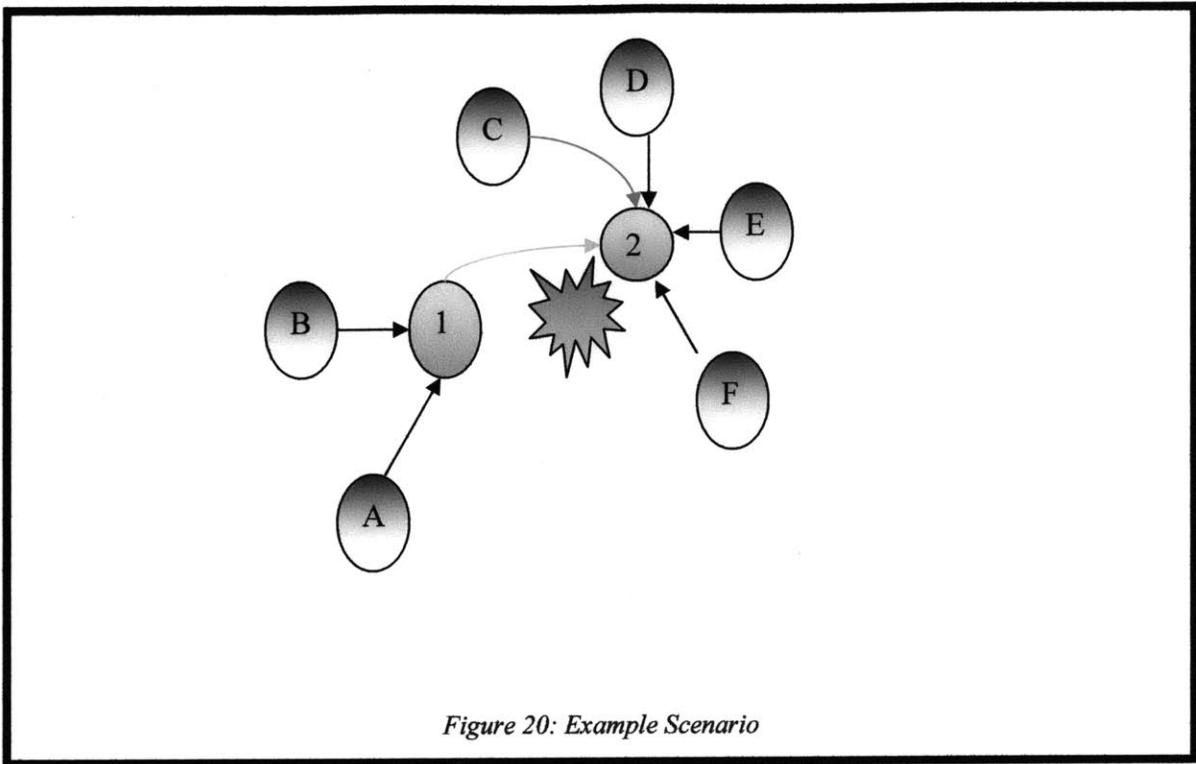
- 1) The location of each city was defined. The individual latitudes and longitudes for each city were randomly generated and their locations were plotted.
- 2) A number was generated to determine the type of city (small, medium, large). There was a one half probability that the result was medium and a one fourth probability for each of the other two possibilities. The overall range of population sizes was ten thousand to one million.
- 3) An increasing exponential distribution for small cities was used to determine the population. A uniform distribution was used for medium cities, and a decreasing

exponential was used for large cities. These distributions were chosen in order to accurately reflect population distributions within many nations including Iran. Every number was generated independently.

It is important to note that an additional test was run using the data on Iran as the input set. This data set was run one thousand times using earthquakes simulated at different locations. The results were markedly similar to those of the general case. Thus, the general case is discussed here. However all of the results here apply to Iran and we talk about the general case since it is easier to show the overall effectiveness and since a large number of simplifications were already made.



The next step was to generate a location for the earthquake. This was accomplished in exactly the same manner that the location for cities was determined. The magnitude was randomly chosen to be 6, 7, or 8 with equal probability. This was done in order to see how the algorithm performed with different magnitude inputs. Below is a visual diagram of a hand generated case containing seven cities. We will discuss how the optimization worked on this specific example below in order to gain some insight into the method:

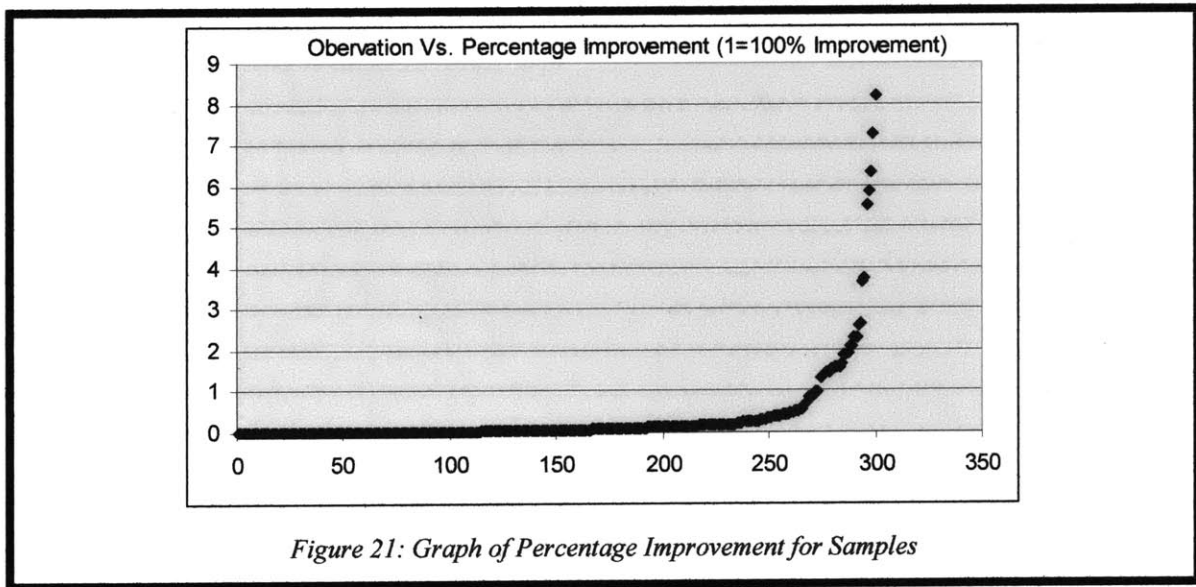


The important characteristics of this simplified random generation are that of the two affected cities. City 2's population is five times city 1's population. Thus the algorithm initially assigns the rescuers from cities A, B, C, and 1 to city 1 and the rescuers from cities D, E, F, and 2 to city 2. The initial output for the number of lives saved is 23,423. The algorithm, however, can clearly improve on this case by sending some of the rescuers currently assigned to city one to city two due to the population discrepancy. The algorithm's solution to this case was to send all of the rescuers from city C to city 2 and although not obvious it is actually optimal to send 76% of the workers from city 1 to city 2 thus abandoning their own. The end result of this trial was that 45,343 lives were saved - almost a 90% improvement over the initial solution. The point to realize here is that the gradient function works methodically to find the exact optimal solution, since we are assuming a smooth hyper plane for the lives saved function.

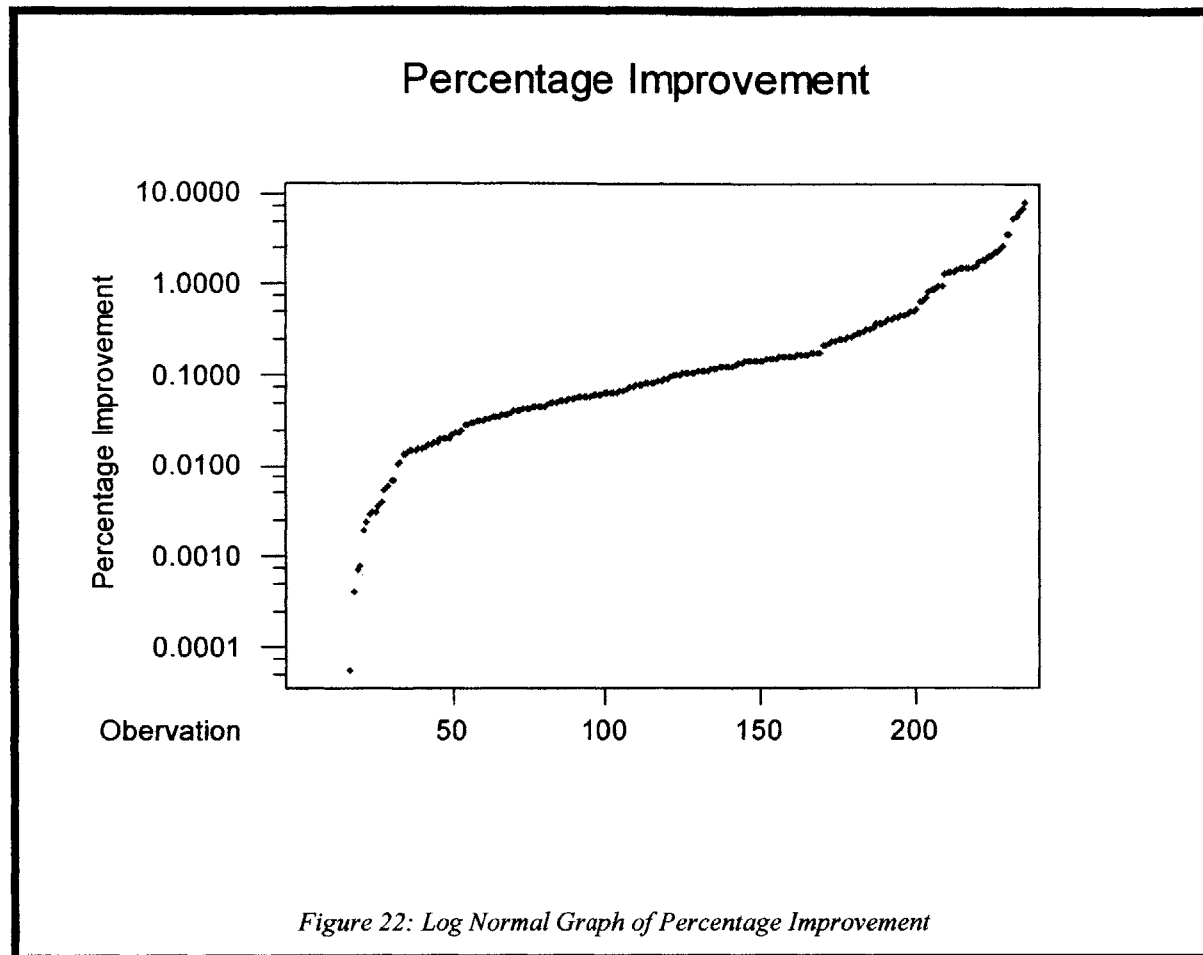
Some Preliminary Results

Thousands of random simulations were run. For each, the percent improvement on the original solution was recorded. Before we discuss the results for these trials, it is necessary to talk about the case of nil improvement. Roughly 20% of the time, the initial distribution was determined to be the optimal distribution. This number was slightly higher than expected and possible reasons for this result will be discussed in a later section. When analyzing the data, however, we often eliminated these cases in order to generate more accurate results. This will be noted. The first graph below shows a random 3000 item sample of the generated results. The data plots the percentage improvement which is defined as:

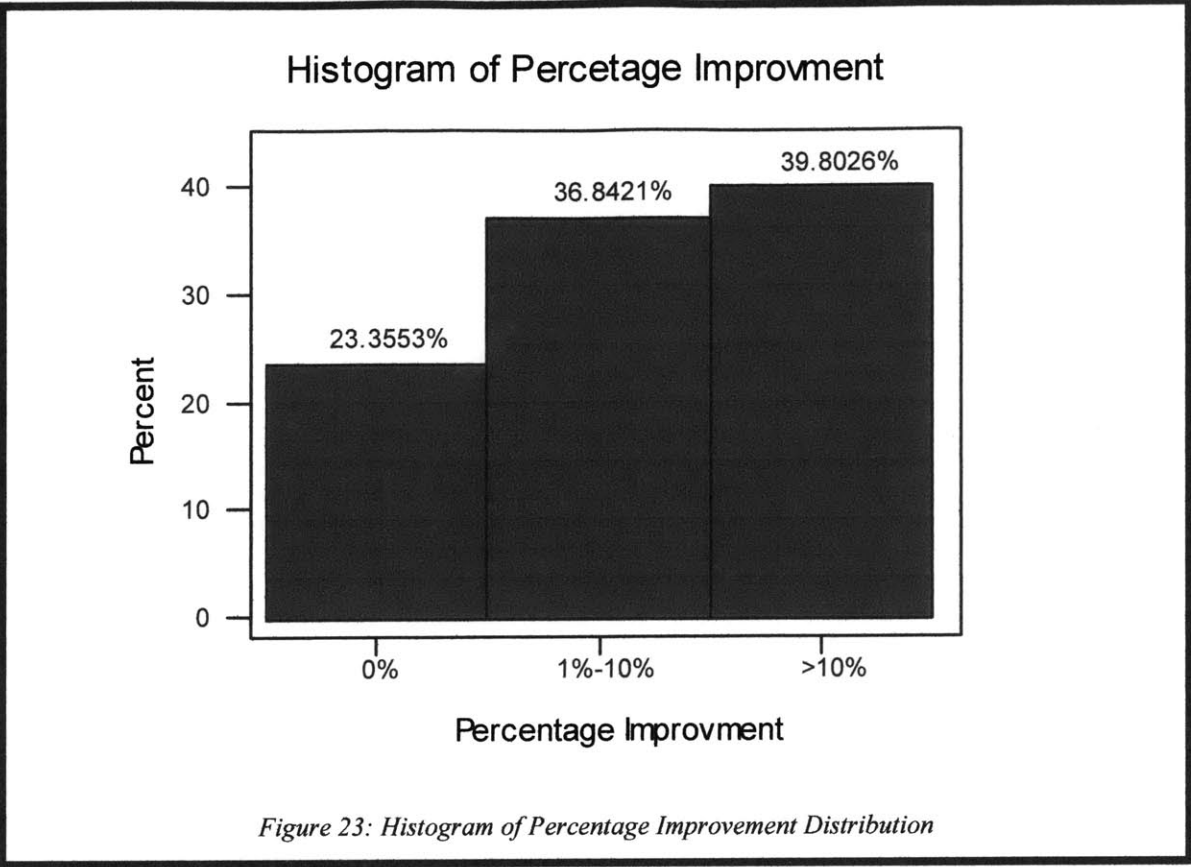
$$\% \text{Im provment} = \frac{\text{FinalNumberOfLivesSaved} - \text{InitalNumberOfLivesSaved}}{\text{InitalNumberOfLivesSaved}}$$



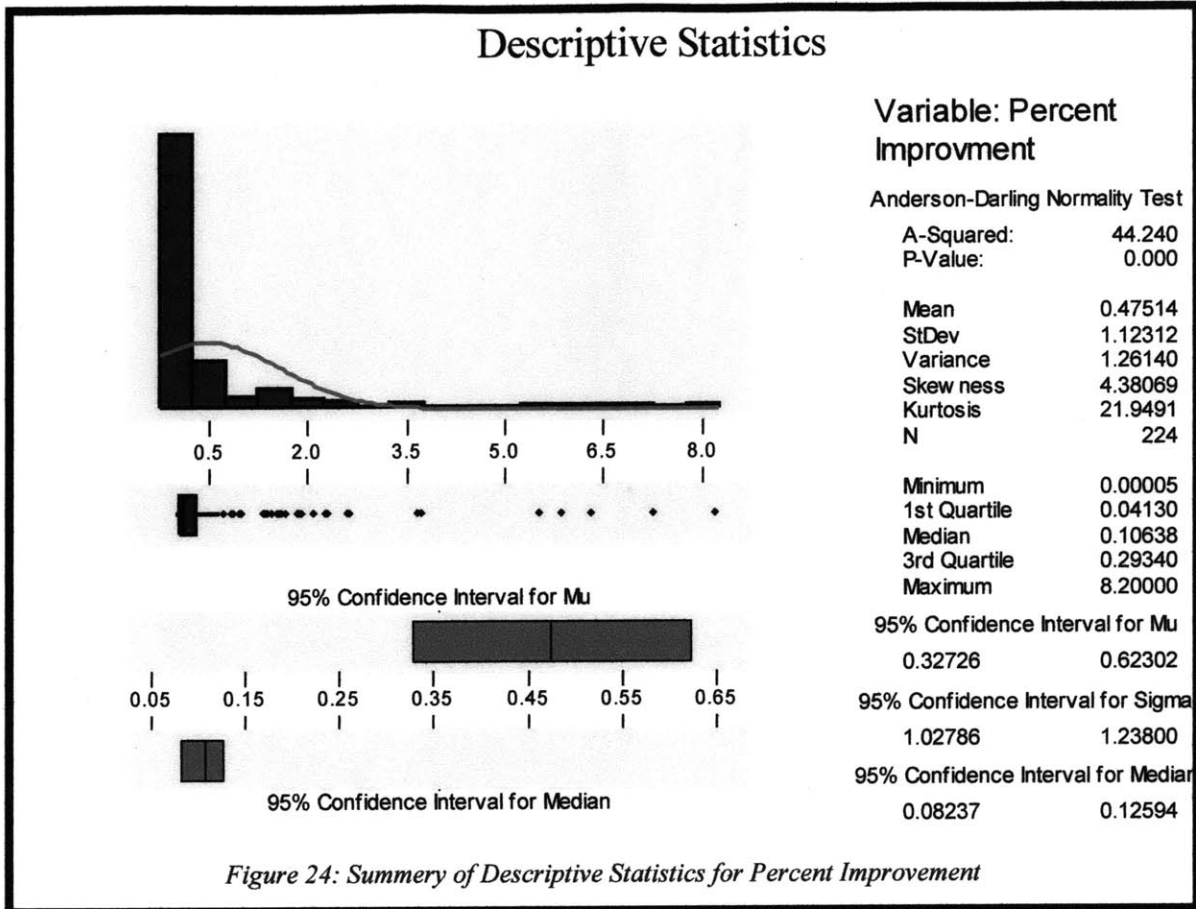
The curve above plots the percentage improvement of each trail, from low to high on a normal scale. In order to fully realize the properties of the curve, it is necessary to examine it in log normal form as shown below (In order to plot on a log scale, the zeros were eliminated).



The first of the two graphs shows somewhat of an exponential curve. From this, we can infer that the majority of the improvements are less than fifty percent. One interesting point to note is the large number of outliers stretching all the way up to a 900% improvement. Overall, we can see a much more descriptive picture when we plot the percentage improvement on a log normal scale. The log normal scale shows a linear center portion with outliers on both sides. From the graph, we see that the percentage improvement is logarithmic, increasing from the fiftieth sample to the two thousandth sample. Now, realizing that the curve shape is exponential, we can calculate some descriptive statistics to further analyze it. Below is a histogram, which classifies the percentage improvement into three categories.



The histogram shows that frequently, optimizing does not help. However, around forty percent of the time there is more than a ten percent improvement. An increase of ten percent or more translates into over 5,000 people on average during a major earthquake. Shown below is a complete picture of the data and its vital statistics (note: the zeros are eliminated from this plot):

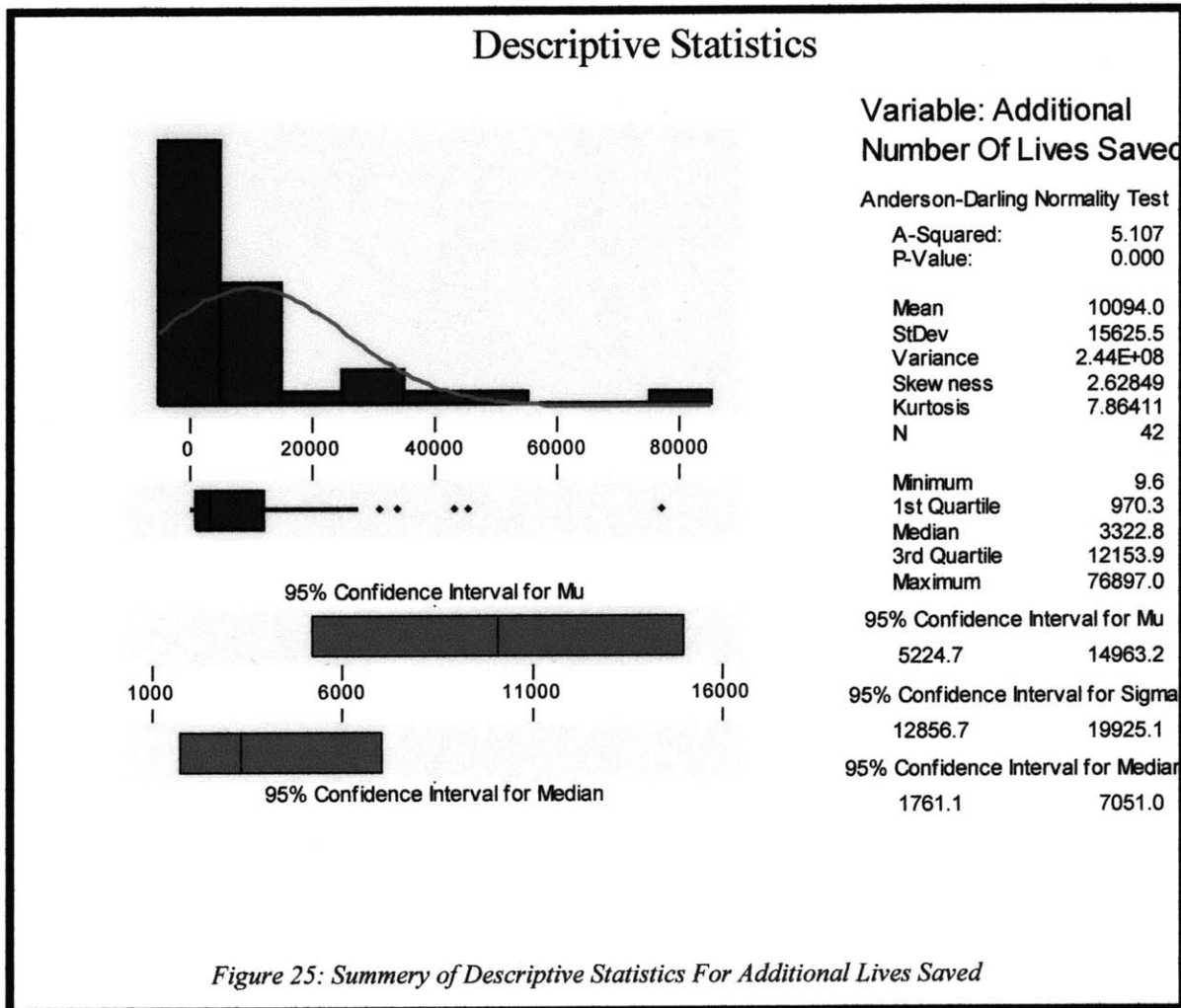


From the first graph in the above diagram, we can see that the skewness factor is very large. It is important to note that only the right hand side is skewed by a large factor. Notice the number of times the percent improvement is greater than one hundred. This indicates that on a significant number of occasions, running this method has a potential to more than double the number of lives saved. Later, we will examine the strength of the earthquakes that generated these results.

The next interesting result is the large difference between the median and the mean. The reason for this is clearly the skewed distribution. While the median is not as large as the mean, notice that the median is a 5+ percent improvement on the original result. This shows that outlier cases are not the only ones demonstrating a significant improvement; rather, over 70% of the time there is a relatively large improvement using the algorithm.

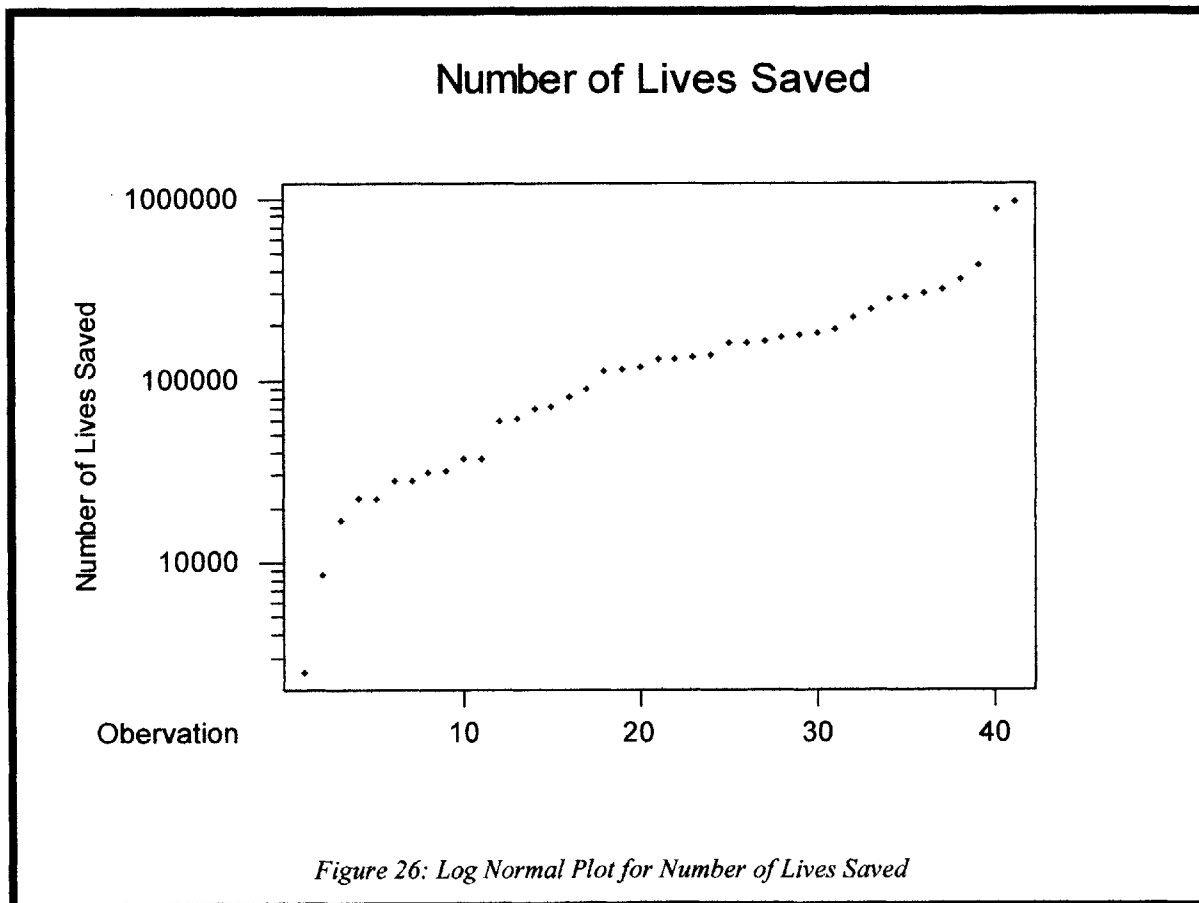
Further Results

The above shows that the algorithm made significant improvements in the percentage of lives saved. However, we are also concerned with the actual number of saved lives along with its gain over the base. This data is shown below with the zero cases once again removed.



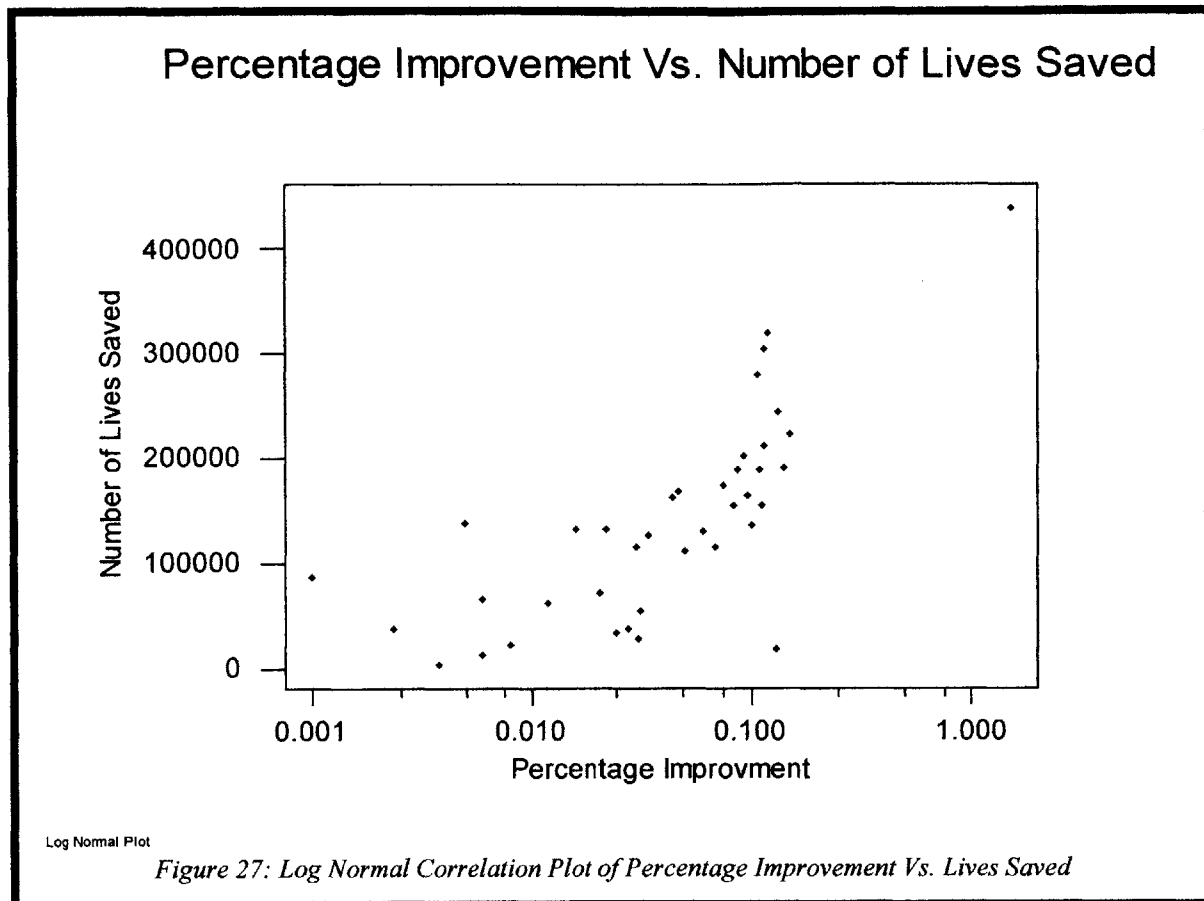
This graph, similar to the previous one, shows a right skewed distribution. The distribution and the outliers shown in the box plot indicate that in some instances, over one hundred thousand additional lives were expected to be saved by using the method. The large mean is explained once again by the outliers. The median, however, is above three thousand demonstrating the tremendous capability of the method.

While we have shown that the algorithm can generate significant improvements, in order to really characterize the amount of improvement the method does, we need to look at the relationship between the percentage improvement and the initial number of people trapped/initial number of people rescued. The reason we will do this is so we can compare where larger and smaller improvements are made and see if they correlate positively with the severity of the earthquake. If we can show that the method makes larger gains during more severe earthquakes then the validity/potential value of the method is further increased. Shown below is the distribution of the number of lives saved in increasing order:



This graph plotted on a log normal scale shows a similar shape to the graph that displayed percentage improvement shown earlier. Thus, this allows us to explore the possibility of a strong relationship existing between the two. In order to determine if there is a positive relationship between percentage improvement and initial number of lives

saved (i.e. a positive relationship between improvement and severity) we must plot the pairs of points on a scatter plot and examine what the correlation is between the two sets. This scatter plot is shown below.



Examining the data set above, there appears to be a strong positive correlation between percentage improvement and severity of the earthquake. It appears that as the number of people trapped increases, the percentage improvement the algorithm accomplishes increases. However, in order to verify this, it is necessary to run a Nemen-Person correlation test between the two data sets. The result when run was $r=0.75346$. This indicates a strong linear relationship between the two data sets. In order to conclude that a relationship exists, it is necessary for the p value to be less than 0.1. When computed for this case, the p value was 0.0 conclusively indicating a positive correlation between the two data sets. Thus the stronger the earthquake, the larger improvement on average the algorithm accomplishes showing the tremendous potential for the method.

Section 8: Conclusion

Sources of Error

Potential sources of error exist in the algorithm due to simplifying assumptions made due to lack of data. One example was the continuous curve that we constructed to estimate the probability of being alive at any point in time within twenty four hours after an earthquake occurs. When earthquake rescuers are attempting to extract trapped people out of debris they usually do not take time to detail statistics on their progress. They do not and should not do this because it takes time away from saving lives that are in jeopardy. Therefore, in order to create such a function, it was necessary to interpolate linear data into continuous data.

Another source of error came from attempting to estimate travel time to a city after an earthquake. Every landscape is different and different factors such as vehicle type, road conditions, time of day, weather, etc. can affect travel times. When we attempted to estimate a travel time function between two cities, we did not have the capabilities to measure or account for all of these conditions. We instead relied on a constant which produced some inaccuracies in the model. If implementation were to occur for a specific location, this data could probably be approximated and measured.

Additional error was introduced when attempts were made to estimate the expected number of lives saved per hour given the population, magnitude, and the number of rescuers. We attempted to incorporate the economies of scale effect, time factor of surviving, the population, magnitude, and amount of work rescue crews do each hour. The effect of any individual one of these factors is difficult to estimate – as a combination, they are nearly impossible. Since we did not have the data available, we created a heuristic that incorporated them. However, the accuracy of the heuristic is difficult to measure. One theorized reason why we had more nil improvements than expected was that we might have over estimated travel time and underestimated the

economies of scale multiplier in the function. Further research can increase the accuracy of these factors.

A final source of error was our rough estimation of the weather and building strength factors. Clearly our gross grouping of cities together is not accurate since each city has a unique building code. One way to make the model more accurate would be to characterize the building strength of each city by examining the building codes, architectural structures and history in order to measure how resistant to earthquake damage a city is. For the weather factor, it is necessary to go over medial studies to determine the effect that temperature has on survival. This would require additional estimation and would rely on non-directly related studies (i.e. people trapped in the cold on a mountain); but, if one was to get an accurate reading of this relationship, the reliability of the model would be greatly increased.

Extensions

In our model, we made the simplification of labeling a constant proportion of the population as rescue workers. In actuality, this is not necessarily the case. For example, cities located near military bases will have more rescue workers available. Regardless of this effect, the question to ask is whether it is optimal to have a constant proportion of each city's population trained as rescue workers. Given the location of a city, what if we could optimize the location of n rescue workers so that they maximized the expected number of lives saved given all the possible locations of earthquakes. This sub-optimization within the large optimization could greatly increase the effectiveness of the method. When completed, the formulation training costs and transportation costs, as well as economies of scale would have to be taken into effect. This improvement in the model could result in thousands of additional lives saved on average. This sub problem is a natural extension to this thesis.

A second extension to this thesis deals with emergency supply locations. Currently, a problem being investigated is locating the optimal location for emergency

supplies in order to maximize the expected number of lives saved. One idea is to locate the facilities along major travel routes so that they will be located along the way of rescuer workers traveling to affected cities. It is vital to locate them away from major cities so that when an earthquake occurs in a major city, the emergency supplies are not destroyed.

Concluding Remarks

Overall, the results show that the algorithm results in a 5% improvement over 70% of the time. The dramatic improvement demonstrated in some test cases along with the high positive correlation between severity of the earthquake and number of lives saved illustrates the potential that the model possesses. At the same time, from a real world perspective, this also highlights the importance of applying optimization techniques to earthquake rescue.

This model can be applied to other real life situations. For instance, with minor modifications, the model is applicable to victims trapped in blizzards or hurricanes as well as to those who are victims of large scale terrorist attacks. Change to the model would merely involve accounting for the amount of damage caused by terrorists as opposed to earthquakes. In our view, the wide range of possible applications warrant further research on this type of model especially during this time of uncertainty.

As far as we know, this two city allocation problem has not previously been investigated. Because of this, there is potential to develop a large scale theoretical mathematical model and to apply it to numerous applications. It is the hope of the authors that the general properties of the model, as well as its applications, be investigated in the near future.

Although Iran has yet to experience an earthquake that caused large scale damage in two major cities, this is clearly no indication that they are immune from the possibility. Due to the extremely poor building codes in the nation development of this

type of allocation in the near future is vital if they are to survive the next devastating earthquake that strikes. Until a method is developed that can accurately predict earthquakes being prepared is the best method we have to minimizing their devastating effects. It is the hope that a model like this one can be implemented in Iran and other nations to help minimize lives lost to the disastrous effects of an earthquake.

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