An Extensible Software Architecture to Facilitate Disaster Response Planning

Martin O'Neill II, Armin R. Mikler, and Tamara Schneider
Center for Computational Epidemiology and Response Analysis, University of North Texas, Denton, TX USA

Abstract— *Disaster mitigation planning must rely on an analysis of available data. However, the vast amounts and different types of data make this data analysis intractable without the use of computational tools. The RE-PLAN Response Plan Analysis framework was designed to create the computational tools needed for these analyses. Although the methodology it employs was originally designed to facilitate validation of mitigation plans for biological emergencies arising from a release of hazardous biological substances, the RE-PLAN framework has been generalized to serve as a launching point for the development of a wide variety of disaster mitigation and evacuation planning scenarios. A tool using the RE-PLAN framework for feasibility analysis of ad hoc clinics for treating the population following a biological emergency event has been created. This paper focuses on the design and implementation of the RE-PLAN framework and how it has been used to address the hazardous biological substance release mitigation data analysis problem.*

Keywords: biological emergencies, disaster mitigation planning, emergency response, evacuation planning, POD throughput, public health preparedness

1. Introduction

The RE-PLAN Response Plan Analysis framework was designed to facilitate the construction of computational tools for the analysis and development of disaster mitigation and evacuation plans. Although this framework was originally designed around a specific disaster mitigation problem, its modules are generalized and may be used in the context of a wide variety of disaster and evacuation situations. Additional modules may be added to the framework in order to address concerns peculiar to specific disaster or evacuation situations. However, the existing framework comprises a significant set of analysis techniques relevant to a wide variety of different situations.

The RE-PLAN framework emerged from a methodology developed for analyzing the feasibility of ad hoc facilities for treating populations following a release of hazardous biological substances [1][2]. A set of facilities is considered feasible if its operational efficiency [3] is capable of meeting service requirements (e.g. specific time frames for service completion or proportions of populations to be served) without exceeding available resources (e.g. transportation network capacities or limitations of facility infrastructure). This paper will highlight the following main architectural components of the RE-PLAN framework and the modules designed to implement them:

- Facility selection and service area determination - Sets of facilities in existing plans may be analyzed or sets of feasible facilities may be generated with respect to the populations' geographic distributions. This component is primarily responsible for the selection of facilities and generation of service areas.
- Logistics calculator - Calculates how the population utilizes the transportation network to travel to the facilities. These calculations facilitate the analysis of conditions on the transportation network resulting from response plan implementation.
- Facility requirement and traffic analysis - Population distribution among the facilities can be examined to facilitate resource distribution, and parking lot entry and exit rates at each facility are determined. Parameters may be modified to increase or decrease the number of individuals each facility is capable of serving per day. Traffic conditions resulting from the placement of facilities may be analyzed using geographic population data, road network data, and traffic count observation data. Parameters such as people per car, time of day, and day of week may be modified to facilitate mitigation planning.

Computational models of biological emergency events show the importance of a policy of aggressive mass treatment [4][5], and delays in this treatment can lead to increased numbers of casualties [6]. Routing and scheduling for timely delivery of medications to treatment facilities have been examined in [7], and strategies regarding medication distribution among the facilities have been explored in [8]. However, the distribution of medications to the population remains a challenging problem [9]. To aid larger cities in planning for these contingencies, the United States Department of Health and Human Services instituted the Cities Readiness Initiative (CRI) in 2004 [10]. An initial evaluation of CRI indicates that the initiative has improved mass treatment preparedness [11]. Studies have been conducted regarding shortcomings and optimization strategies inside service facilities during a biological emergency [12][13]. However, less attention has been paid to how the population will be delivered to facilities for treatment during response plan implementation.

Surveillance systems, such as the BioSense system created by the Centers for Disease Control and Prevention [10], use data from disparate sources to facilitate early detection of biological emergency events. The World Health Organization endorses the use of public health surveillance systems, referring to them as being, “the cornerstone of public health security.” [14] A wide variety of different data sources such as over-the-counter drug sales [15][16], internet search query patterns [17][18], and personal web log (blog) data [19] have been explored to detect public health events. However, further exploration of available data sources to allow decision makers to develop and analyze their response plans is needed [12].

Disaster mitigation and evacuation planning must rely on an analysis of quantitative data [20]. However, the vast amounts and different types of data make this analysis intractable without the use of computational tools. A set of generalized modules was designed around data analysis problems relevant to a variety of disaster mitigation and evacuation planning and analysis. These modules, which facilitate the analyses of many different types of geographic, spatio-temporal, and demographic data, comprise the RE-PLAN Response Plan Analysis framework.

2. Plan Analysis Problems

A feasible response plan must be able to accomplish its assigned tasks without exceeding the available resources. The assigned task of facilities hosting ad-hoc clinics in a biological emergency is to serve the entire population within specific time frames. This facility throughput problem may be affected by geographic population distribution and facility location, constraints of the transportation network, limitations of the facilities, and the availability of personnel and supplies. All of these factors can be separated into two groups: problems that may occur at the facilities themselves, and problems that may occur in each facility’s service area.

2.1 Problems at the Facilities

The primary question to be answered when analyzing problems that may occur at a facility is, “Can the facility serve the number of people in its assigned population under the given time constraints?” To answer this question, the service area of each facility must be determined. Once the service areas have been determined, the population of each service area may be analyzed to estimate the requirements of each facility. These requirements lead to further questions such as:

- “Can the parking lot at each facility support the number of cars which must enter and exit under the time constraints?”
- “How long will it take for each facility to serve its assigned population?”
- “Based on the assigned population of each facility, are there any special requirements for the facilities?”

2.2 Problems in the Service Areas

The population in each service area is unlikely to be uniformly distributed. Further, transportation network infrastructure is likely to be irregularly distributed across the service areas. Therefore, the locations of the facilities in relation to population distribution and transportation network resources must be examined. A facility may be capable of serving its assigned population under the time constraints. However, if the transportation network is incapable of delivering individuals to the facility in a timely manner, resources at the facility may be under-utilized. This motivates the question, “How will the implementation of the facilities in a given plan affect the traffic situation on the transportation network?”

3. Methodology

The methodology employed by the RE-PLAN Framework was designed to analyze plan feasibility using large amounts of quantitative data from disparate sources. These data include population data, transportation network data, and traffic count observation data. Combined with assumptions from public health officials, this methodology is used to create a model which facilitates the analysis of conditions resulting from the implementation of response plans. Further, the model allows public health officials to experiment with alternate plan scenarios while exploring the data underlying the computational model.

3.1 Facility Selection and Service Area Determination

A variety of facility selection and service area determination methods have been developed. The most simple method allows users to select facility locations directly and then uses these locations as a basis for determining service areas. A variation on this method allows the user to select a set of facility locations and to set the number of desired facilities. The most feasible of the selected facility locations are then automatically determined, and service areas are created based on the locations of these facilities. Yet another method creates uniform service areas based on selected demographic variables. Once the service areas have been created, the facility locations are selected within them.

3.2 Service Facility Analysis

Once service areas have been determined for each facility, the population assigned to each is also known. Each facility’s requirements and feasibility can then be analyzed with respect to the population it is assigned to serve. Depending on the outcome of this analysis, users may choose to redistribute personnel and resources among the facilities or to modify their response plans. Methods for analyzing the set of facilities include examining the distribution of the population among them, calculating the amount of time it will take for each to serve its assigned population, and estimating the traffic situation in each's parking lot.

Decisions regarding the distribution of personnel and supplies among the facilities requires an analysis of the distribution of the load (in this case, the population) across the set of facilities. Facilities assigned a greater load must be assigned more personnel and resources to adequately handle this load. Those assigned drastically smaller or larger loads can be identified, allowing public health officials to adjust their response plans accordingly. Once the distribution of load across the set of facilities is acceptable, and personnel and resource distributions have been determined, analysis can continue.

The estimated service time T_i required for each facility i to serve its assigned population p_i can be calculated by $T_i = \frac{p_i s}{w_i}$, where s is the amount of time it would take to serve a single individual and w_i is the number of individuals who may be served at facility i in parallel. Any facility whose estimated service time is close to or exceeds the mandated time constraints may be infeasible. The feasibility of a particular facility may be improved by increasing the number of individuals whom it may serve in parallel, by decreasing the assigned population, or by shortening the amount of time it would take to serve a single individual.

The total number of cars a_i which must visit each facility i can be calculated by $a_i = \frac{p_i}{f}$, where f is the average number of people who will travel in each car. This average is determined by public health officials and may be based upon such factors as demographic data or familiarity with the population to be served. The rate r_i at which cars must enter and exit the parking lot at each facility i can be calculated by $r_i = \frac{T_i}{a_i}$. Further, the rate ρ_i at which cars must enter and exit each parking lot in order to meet the time constraints ω can be calculated by $\rho_i = \frac{\omega}{a_i}$.

3.3 Traffic Analysis

If the transportation network of a service area is incapable of delivering the population to the facility in a timely manner, the facility will be under-utilized, causing it to be infeasible. Therefore, the traffic situation resulting from implementation of specific response plans must be analyzed. To accomplish this task, a model of how the population travels inside each service area must be used. This model must combine geographic population distribution data with transportation network data into a context which facilitates the analysis of traffic conditions at specific points inside each service area.

If each service area is divided into rings around the facility as shown in Figure 1, the population of the outer rings must travel through the inner rings to arrive at the facility as shown in Figure 2. Further, it must also travel back through these inner rings to return to its origin. Each ring of the service area may then be divided further into a series of segments around links in the transportation network which connect them as shown in Figure 3. The population of the outer rings may then be modeled crossing from segment to segment on its way towards the facility. The links on the road network, shown in Figure 4, where the population crosses from ring to ring may be examined with respect to the number of individuals who must cross these links.

The population crossing each link may be divided by the average number of individuals per car to determine the load on each link caused by the implementation of the plan under the time constraints. The constraints of the transportation network are likely to vary. Therefore, the load caused by the implementation of the plan at a specific point must be analyzed with respect to the properties of the transportation network at that point (e.g. speed limit, number of lanes, functional class, or maximum physical capacity).

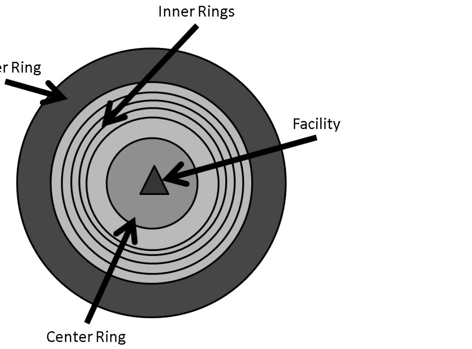

Fig. 1: Breaking a service area into rings of proximity to the facility

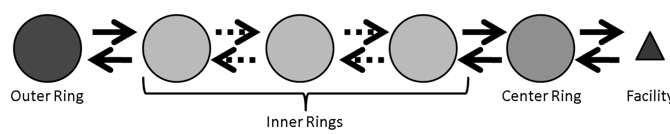

Fig. 2: How the population travels through the rings of proximity to the facility

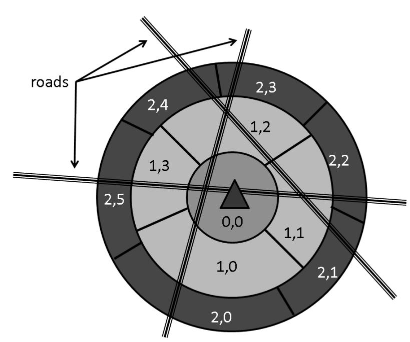

Fig. 3: Using only three rings of proximity, dividing rings into segments to model population flow across roads

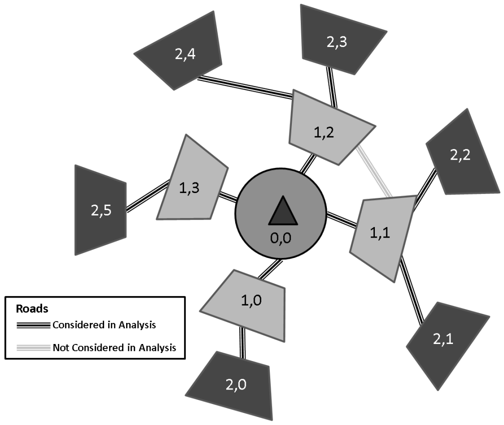

Fig. 4: Using only three rings of proximity, links in road network where population must cross from one ring to another are examined.

Disasters do not occur in a vacuum. Traffic to the facilities will not be the only load on the transportation network. This necessitates the analysis of normal "business as usual" base traffic side-by-side with traffic to the facilities. To accomplish this task, traffic count observation data must be used with other properties of the transportation network to project the load of base traffic across the network. Further, time-of-day and day-of-week become important considerations when dealing with base traffic to adequately represent peak and off-peak traffic periods.

4. RE-PLAN Framework

The RE-PLAN Architectural Framework consists of the Plan Designer, Plan Analysis Tools, and the Logistics Calculator. These three main architectural components communicate with the RE-PLAN Database to facilitate plan creation and analysis. Each component consists of a series of modules which may be redesigned, augmented, or replaced in order to change the underlying model being used. The work flow diagram in Figure 5 shows an overview of how the modules are used in each of the architectural components to design plans, calculate logistics, and perform analysis.

4.1 Plan Designer

The Plan Designer allows the user to create a response plan consisting of a set of facilities and assigned service areas. Figure 5 shows three different example paths through the modules of the Plan Designer. Each of these paths results in a set of facilities and service areas being stored on the RE-PLAN Database. The flexibility of these modules lies in the specific tasks they were chosen to perform.

The Facility Editor module allows users to create, edit, delete, import, and export facilities. All of these functions are accomplished through a point-and-click graphical interface. This module modifies the RE-PLAN Database as the user modifies the facilities in a plan. The information regarding each facility which currently affects the plan analysis calculations are the facility's longitude, latitude, type, status, and width. The longitude and latitude are used to specify a facility's geographic location. A facility's type may be used to modify how a facility affects logistical calculations or analysis of a plan. A facility's status reflects whether it is *on* or *off*. Only facilities which are *on* are included in the logistic and analysis calculations. The width of a facility is the number of individuals which may be treated at this facility in parallel. Additional information (such as name, address, and comments) may be stored with each facility to assist officials in their planning, but this information is not used in the logistic or analysis calculations.

The Automatic Facility Selector module chooses locations for a user-specified number of facilities. If a list of facilities has already been chosen, this module selects the number of facilities from them. Once facilities have been selected, the Creator of Service Areas for Facilities module breaks down the area of interest such that every point in the area of interest is assigned to exactly one facility. Once these facilities and service areas have been determined, they are stored in the RE-PLAN Database.

The Creator of Uniform Service Areas module breaks down the area of interest into uniform service areas based on the demographic characteristics of the area's population. After the service areas have been created, feasible facility locations are selected for each service area. Once the service areas and facilities have been determined, they are stored in the RE-PLAN Database.

The POD Analysis problem was examined and broken down into a series of modules which comprise the RE-PLAN tool. Together with the RE-PLAN database, these modules facilitate the analysis of POD-based biological emergency response plans.

4.2 Logistics Calculator

Once a plan has been created by the Plan Designer and stored in the RE-PLAN Database, the Logistics Calculator prepares this plan for analysis. Each facility's service area is dissolved into rings of proximity. Each ring is dissolved into a series of segments around crossing points where links in the transportation network connect the rings, and the population of each segment is calculated. The population is then cascaded across the crossing points leading to the facility such that the number of individuals who must traverse each crossing point to reach the facility is known. The crossing points are stored in the RE-PLAN Database with their corresponding loads (in numbers of individuals).

4.3 Plan Analysis Tools

The Plan Analysis Tools facilitate analysis of response plans at the facility and on the transportation network. The Facility Requirement Analyzer module uses data from

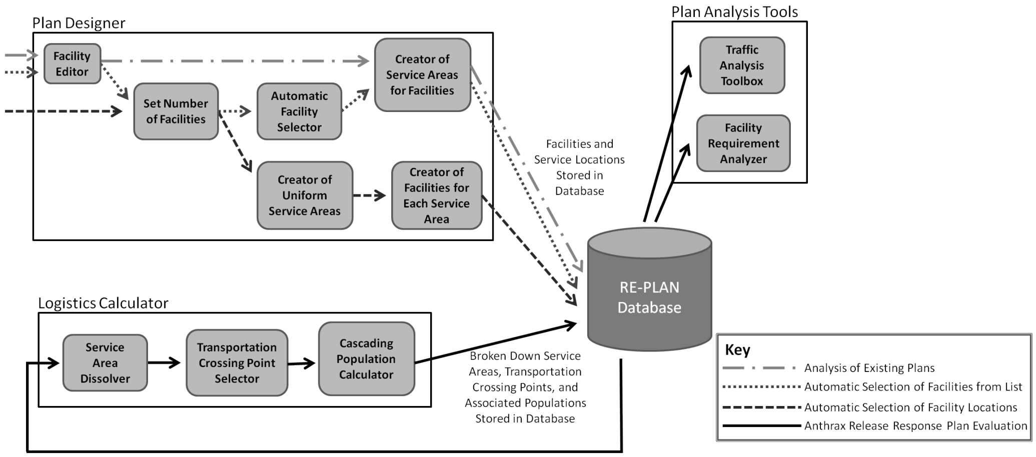

Fig. 5: RE-PLAN Framework Architectural Components and Work flow Diagram

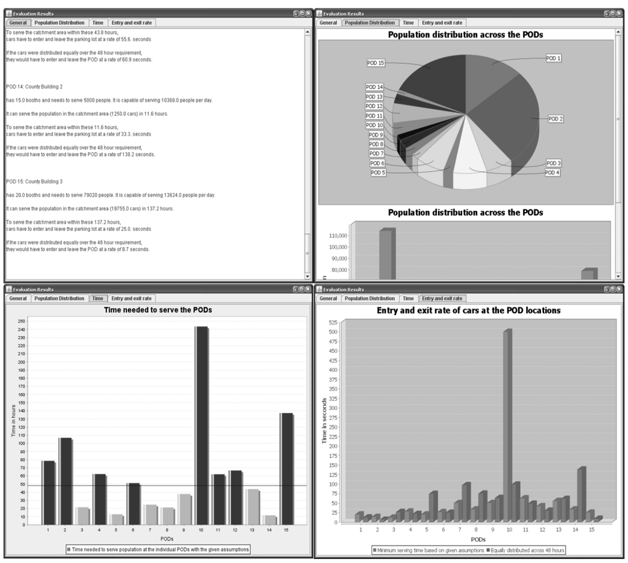

Fig. 6: Facility Requirement Analyzer graphical display

the RE-PLAN Database created by the Plan Designer to explore the expected situation at each facility. The Traffic Analysis Toolbox module uses data from the RE-PLAN Database calculated by the Logistics Calculator to facilitate exploration of traffic conditions resulting from response plan implementation. Although these modules are functionally separate, they comprise the set of analysis tools available in the RE-PLAN Framework.

4.3.1 Facility Requirement Analyzer

The Facility Requirement Analyzer module facilitates the analysis of response plan data created by the Plan Designer through a series of four tabs shown in Figure 6. Graphical representations of population load distribution among the facilities are created, allowing public health officials to easily analyze personnel and supply distribution requirements of the facilities. Further, the population load on each facility is combined with user-specified assumptions regarding the width of each facility, the average number of people who will travel to the facility in each car, and the amount of time required to serve each person to create graphical representations for the analysis of each facility.

The first of the four tabs provides a written report for the entire plan and for each individual facility. The second tab includes two different graphical representations of the population distribution. The third tab shows the time required for each facility to serve its population under the current assumptions. Facilities which are capable of serving their populations within the mandated time constraints may be considered feasible and are shown in green while their infeasible counterparts are shown in red. The fourth tab shows estimates of the situation in each facility's parking lot under the mandated time constraints as well as under the total amount of time required for each facility to serve its assigned population.

4.3.2 Traffic Analysis Toolbox

The Traffic Analysis Toolbox module combines geographic population data with transportation data in the context of the response plan logistics data. Traffic conditions at specific points may be examined with respect to the physical properties of the transportation network and the load on these points resulting from "business as usual" base traffic, traffic caused by implementation of the response plans, or a combination of both. Traffic conditions at each point are classified into one of six different classes which represent the ratio of load to the maximum physical capacity. Figure 7 shows how these classes are visually represented on a map to facilitate analysis of traffic conditions by personnel without the need for Geographic Information Systems (GIS) or computer programming expertise.

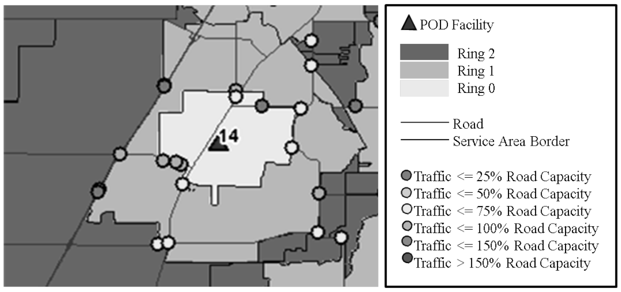

Fig. 7: Screen capture of traffic analysis using RE-PLAN hazardous biological substance release mitigation plan analyzer tool

Fig. 8: Traffic toolbox interface for analysis of Point of Dispensing (POD) facilities for hazardous biological substance release mitigation plans

The Traffic Toolbox graphical interface in Figure 8 allows users to easily change analysis parameters through a point-and-click interface. Traffic resulting from implementation of response plans and base traffic may be toggled *on* or *off* independently. Parameters which affect base traffic projections such as *weekday* versus *weekend* traffic and *time of day* may be adjusted. Assumptions which affect response plan traffic such as *people per car* and time constraints may also be adjusted.

4.4 RE-PLAN Database

The RE-PLAN Database stores all information about the response plans. It is also the primary way data is shared among the different architectural components of the RE-PLAN Framework. Three main categories of data are stored on the RE-PLAN Database: data concerning the area of interest, data which comprises response plans, and other data which facilitates the user experience and collaboration among users.

Data concerning the area of interest must be loaded into the RE-PLAN Database before plan creation or analysis begins. This includes spatial demographic and population data, spatial transportation network data, and traffic count observation data. If traffic count observation data is unavailable for the area of interest, data from another area may be loaded and used to train the Traffic Analysis Toolbox module. Data for multiple areas may be loaded into the RE-PLAN Database, and users may adjust parameters to choose a specific area of interest among them.

The RE-PLAN Database also stores all data resulting from the creation and analysis of individual response plans. The set of facilities, their service areas, and the load distributed across the transportation network are all stored in the database. For each facility, the facility's name, location, address, city, zip code, status, type, and other comments are stored in the database. If the Logistics Calculator has been used on a response plan, the dissolved service areas and population load on the transportation network are also stored in the database. Notes about each plan may also be stored with each plan in the database.

Each plan is owned by a specific user, and this association is stored in the RE-PLAN Database. This facilitates collaboration among users who may share their plans. Data concerning the currency of response plans is stored for the purpose of automatically deleting temporary database tables. Further data regarding the analysis progress of each response plan is also saved to enable RE-PLAN tools to open saved plans with the correct options and features enabled. For example, if a plan was saved before the Logistics Calculator was executed, when the plan is reloaded, the Traffic Analysis Toolbox should not be available to the user until the Logistics Calculator is executed.

5. Implementation

The RE-PLAN framework employs a client-server model. Client-side modules are written in Java for portability, and a PostgreSQL database with PostGIS is used on the RE-PLAN server for flexibility. This model facilitates collaboration among users whose client programs connect to the same server, thus allowing users to access each other's mitigation plans. Further, the client programs have minimal system requirements since most of the complex calculations are executed on the server. As a result, new hardware may not have to be deployed to execute the client programs.

Modules in the framework have been designed to be interoperable by incorporating import and export features. Sets of facilities may be imported or exported as Comma Separated Values (CSV) files. Many software packages commonly used in public health, disaster management, and city planning are capable of importing and exporting data as CSV files. Therefore, existing data may be imported into tools created with the RE-PLAN Framework and exported to other commonly used software packages.

Functionality to export entire plans as standard ESRI shapefiles allows data to be shared and further analyzed by those with GIS expertise. These plans may be published by creating maps in software packages such as ArcGIS or may be used to create online, interactive maps using OpenMap, Google Maps, or Microsoft Bing Maps. Therefore, the RE-PLAN Framework facilitates not only plan analysis, but plan distribution and implementation as well.

6. Discussion

The hazardous biological substance release mitigation tool created using the RE-PLAN Framework answers important questions regarding the implementation of specific response plans. The tool harnesses large amounts of quantitative data to estimate conditions at and requirements for each facility during implementation of specific mitigation plans. These conditions and requirements include the projected traffic situation at each facility's parking lot, the amount of time each facility requires to serve its assigned population, and the infrastructure needed by each facility to serve its assigned population. Further, the tool facilitates the analysis of the traffic situation on the transportation network resulting from the implementation of specific response plans.

The RE-PLAN Framework was developed in collaboration with public health officials. Their suggestions and comments were included in the methodology and implementation. Graphical interfaces were incorporated into the framework to allow use without the need for GIS or computer programming expertise. Although large amounts of quantitative data are used and may be accessed through the Framework, the design of graphical displays focused on specific aspects of the response plan analysis methodology. Therefore, while the data underlying the computational model may be accessed through the graphical interface, it is hidden by default to avoid clutter and confusion.

A version of the hazardous biological substance release mitigation tool has been created and deployed at a local county public health department. County public health officials have been trained to use this tool for analyzing their mitigation plans. Analysis performed at the county using this tool has lead to the revision and modification of response plans. Local stakeholders have been trained regarding the modified plans, and preparations to implement these plans are underway.

The RE-PLAN Framework is comprised of a set of generalized modules. These modules may be used together in different contexts to address different response or evacuation scenarios. The methodology used may be adjusted by modifying existing modules, and additional modules may be created to address problems peculiar to specific scenarios. Further, the existing framework may be used to create tools with a web interface, thus enabling widespread distribution of RE-PLAN tools.

7. Limitations

As with all computational models, fidelity is limited by the accuracy and availability of underlying data sets. The RE-PLAN Framework uses several sets of data for which availability or currency may be problems. Examples of these data sets are population data, transportation network data, and traffic count observation data. Nonetheless, the RE-PLAN Framework has been developed to be as flexible as possible in accepting alternate data sets.

Geographic population distribution data is available in the United States from the U.S. Census Bureau. However, a full census is only conducted once every decade, leading to the use of potentially out-of-date data. If more accurate or current population distribution data is available from other sources, the RE-PLAN Framework is capable of incorporating this data into the model. The only limitation regarding which population distribution data may be used is that the framework is only designed to incorporate vector (not raster) data sets. However, raster data can easily be transformed into vector data using a wide variety of available tools.

Transportation network data may be incomplete or out-of-date for certain areas. Smaller neighborhood roads may be excluded from available data sets. However, these smaller roads do not greatly affect traffic analysis. Although newer links on the transportation network may not be included in available data, local public health officials who are using the tool will likely be familiar with the roads in their area. Attributes available for each link of the transportation network may differ from location to location. To address this problem, a variety of methods have been developed to use the framework with the available attributes.

Traffic count observation data may be unavailable for the vast majority of links in the transportation network. The RE-PLAN Framework addresses this sparse data problem by classifying the links in the transportation network and assigning links of the same class the same traffic loads. Traffic count observation data may contain inaccuracies due to the methods used in the collection of this data. If this data is too sparse or entirely unavailable for an area, the RE-PLAN Framework may be trained on data from a similar, but different, area. Nonetheless, it may not be difficult to accurately determine whether a specific traffic count represents conditions of high traffic speed and low traffic density, or of low traffic speed and high traffic density.

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