A Prototype Desktop Simulator for Infrastructure Protection: An Application to Decision Support for Controlling Infectious Disease Outbreaks

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Abstract –

The Critical Infrastructure Protection Decision Support System (CIPDSS) project has developed a risk-informed decision support system that provides insights for making critical infrastructure protection decisions by considering many critical infrastructures and their primary interdependencies. Initiated as a proof-of-concept in August 2003, the CIPDSS project completed a prototype model and two case studies in February 2004, using a system dynamics implementation. Since that time the project has demonstrated how the CIPDSS can assist decision makers in making informed choices by functionally representing key critical infrastructures with their interdependencies, and computing human health & safety and economic impacts. The method of delivery to date has involved the conduct of analysis by the project developers and delivery of the results in the form of reports and presentations, often supplemented with face to face interactions with sponsors and decisions makers. This approach benefits from having the analysis conducted by the developers who best understand the underlying models and their limitations. However, this mode of delivery can be said to live more distant from those who might best benefit from being exposed to the analysis and the inherent trade-offs therein. This paper describes the development of a desktop simulation designed to help bridge this gap between the CIPDSS models & analysis and decisions makers. To illustrate the utility of this approach, an application focused on controlling infectious disease outbreaks, such as Pandemic Influenza, has been implemented.

INTRODUCTION

The Critical Infrastructure Protection Decision Support System (CIP/DSS) simulates the dynamics of individual critical infrastructures [1] and couples separate infrastructures to each other according to their interdependencies [2]. For example, repairing damage to the electric power grid in a city requires transportation to failure sites and delivery of parts, fuel for repair vehicles, telecommunications for problem diagnosis and coordination of repairs, and the availability of labor. The electric power grid responds to the initial damage and to the completion of repairs with changes in its operating characteristics. Dynamic processes like these are

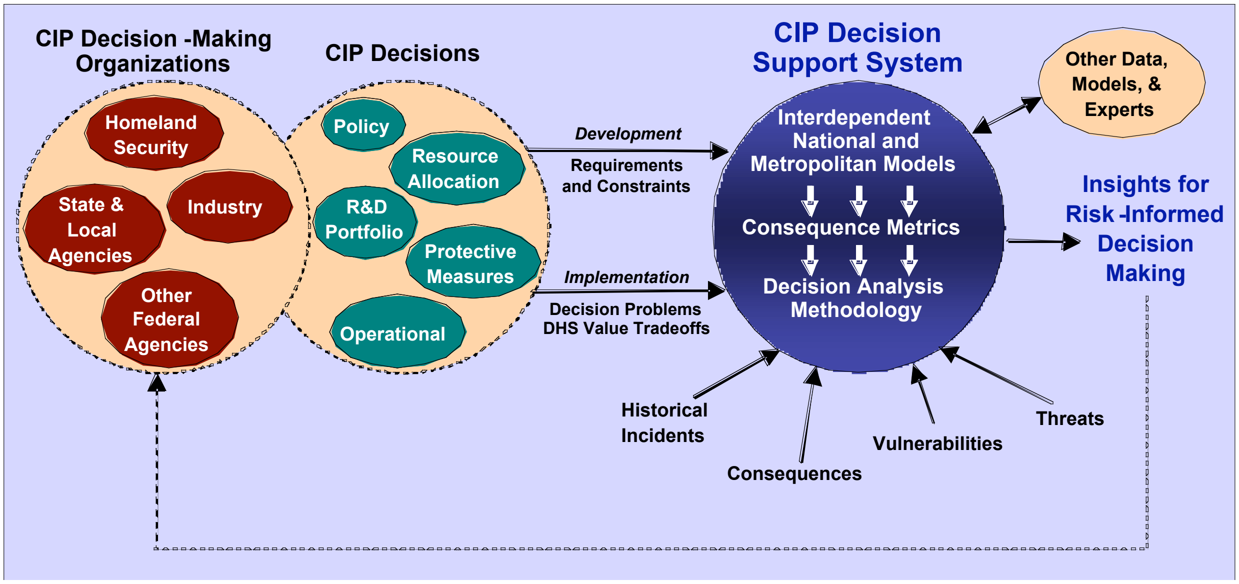


Figure 1: Relationship between CIP decision makers, decisions, and the CIP/DSS.

represented in the CIP/DSS infrastructure sector simulations by differential equations, discrete events, and codified rules of operation. Many of these variables are output metrics estimating the human health and economic effects of disturbances to the infrastructures. These models are implemented in system dynamics using Vensim™ [3] which reads input parameters from and writes output time series of "consequence" metrics to an Oracle™ relational database. These metrics are abstracted into a much smaller set of "decision" metrics.

An understanding of the disturbances that might impact critical infrastructure operations is also a key to understanding the potential impacts on infrastructures and mitigation actions taken to moderate or eliminate the effects of the disturbance. Disturbances such as physical disruptions, infrastructure demand overload as well as the introduction of biological threats (such as a pandemic influenza) or chemical threats (such as an accident at a chemical plant) have been modeled with additional disturbance types being contemplated. As such CIPDSS has found it important to model these events and potential mitigating actions and integrate those models with the infrastructure models so that the feedback between the events, infrastructures and mitigating policies can be included.

Decision makers need to understand the consequences of policy and investment options before they enact solutions, particularly for the highly complex alternatives available for protecting our nation's critical infrastructures in today's threat environment. To that end the CIPDSS coupled infrastructure and scenario models are integrated into a decision support system that incorporates potential mitigations and disruption consequences in quantitative analyses (see Figure 1). This system has provided support to decision makers in a variety of areas over the last three years including for pandemic influenza [4, 5, and 6], hurricane Katrina [7], and telecommunications [8]. Government (federal, state, local) and industry decision makers can make use of this system to prioritize protection, mitigation, response, and recovery strategies as well as to support red-team exercises and provide support during crises and emergencies.

To date this support has been provided in a process where questions are asked of the CIPDSS team, typically related to the potential impact of a disruption on infrastructures and possible mitigating policies, models are modified as needed and analysis performed by the developers and provided to decision makers in the form of reports and presentations. Often preliminary analyses are presented that suggest additional questions and analyses that are incorporated into the final product. This delivery approach benefits from the knowledge that the models are used by developers that understand the relationships, assumptions and limitations inherent in any model. However this approach also necessitates a certain distance between the analysis and the decision maker. Significant time elapses between question and answer during which the data used, assumptions, and trade-offs made are largely invisible to the ultimate user of the analysis. Much of the learning process, the twists and turns of the analysis and sensitivities and uncertainties to assumptions and inputs experienced by the developers are largely unseen by the policy maker. In many cases the questions asked and the answers uncovered would benefit greatly if the decision maker were more closely involved in the analysis experience.

This decision maker support process could be improved in many cases with the use of a simulator that incorporates the infrastructure, disruption and mitigation models of CIPDSS coupled to an interface that allows a user to manipulate policies and assumptions and view relevant metrics of the outcomes. Such a system could close the distance between decision maker and analysis where a decision maker or group of decision makers can directly manipulate and observe the effects of changes to assumptions about the characteristics of the disruption, the operation of critical infrastructures and their policy options - increasing the learning in the entire developer – policy maker 'system'.

Fortunately there is a great deal of experience in the system dynamics community with these types of simulators, alternately known as learning environments, flight simulators and microworlds [9, 10] which are natural extensions of the system dynamics methodology. These types of simulators have been applied in a variety of applications including for example, banking [11], public health [12, 13] and port security [14]. An excellent review of these applications is given in reference [15]. CIPDSS, being largely based on system dynamics methodology and motivated to bring the analysis capabilities closer to the decision and policy makers has therefore embarked on developing a simulator, leveraging the extensive experience available in the SD community. We are beginning with a prototype version described herein that can be used to explore various approaches to the simulation and obtain feedback from potential users. This prototype version was developed using the Sable development environment from Ventana Systems, UK [16]. Sable is designed for the rapid development of interfaces for models developed with Vensim and can leverage Venapp Builder [17] and several scripting languages to expand its built-in capabilities.

We chose to focus the prototype on biological threat applications, such as the consequences of a Pandemic Influenza outbreak, because they have the potential to exercise many of the key features of the CIPDSS models while being of clear current relevance [18]. The prototype simulator exemplifies the simulation of possible pandemic outcomes on critical infrastructures, public health outcomes and economics based on the best possible data and information available [19 – 22]. Other infectious diseases such as plague and the Marburg virus are also available.

The core infectious disease model in the desktop simulator can easily be adapted and applied to any infectious disease.

We continue now by first giving a few snapshots of the CIPDSS models to provide context and then follow that with a description of a group brainstorming session used to determine an initial set of desirable features for the simulation. Finally the current state of the prototype simulator is described in some detail.

CIPDSS MODELS

The infrastructure consequence models simulate the dynamics of individual infrastructures and couple separate infrastructures to each other according to their primary interdependencies. Each critical infrastructure sector is divided into a number of sub-sectors that have a more uniform character and for which separate Vensim™ views are developed. For example, the emergency services sector is divided into 1) fire services, 2) emergency medical services, 3) law enforcement, and 4) emergency support services. A custom-built Vensim™ model "linker" called the 'Conductor' is used to assemble a unified multi-sector models from individual files each containing a single sector model as well as to do numerous syntax checks. The linker identifies "shadow variables" present in models with dependencies on other sectors and resolves the references when the models are combined. This allows us to develop and test models at the sector level, but run analyses at the multi-sector level.

The type of model chosen for each sub-sector depends on: 1) the characteristics of the particular infrastructure domain; 2) the data available to populate the model parameters; 3) questions to be asked of the model; 4) the amount of time available for development; and 5) any software constraints. Below are short descriptions of one of the critical infrastructure models (public health) and the infectious disease model that represents the disruption or scenario model for the prototype simulator. This provides a flavor of the types of models involved, typical output metrics and inputs and policies that will be exploited by the Sable interface. More detailed discussion of the public health and other sector models are given elsewhere, for example [23].

Metropolitan Public Health Sector

This model is required to represent the main activities of the Public Health sector and its primary interdependencies with other infrastructure sectors. The ability of the system to respond to emergency situations, such as natural disasters, terrorist attacks, large-scale accidents, or other unanticipated events is of particular interest. The system estimates the number of patients treated, the treatment outcome categories, the dispositions of patients, and costs of care. Other metrics of public health care may be calculated as appropriate. The dependence of the system on other infrastructures, for example, water, food, energy, government, transportation, banking, etc., is integrated into the overall system model. The system is capable of expanding its treatment capacity to accommodate the patient load on the system. If necessary, the system must be able to draw on regional and national resources (such as pharmaceutical stockpiles), as well as create facilities for treatment, prophylaxis, and quarantine, as needed. The Public Health sector also interacts closely with the Emergency Services sector, accounting for the effect of emergency situations on the public health and emergency services labor force and any reduction of their capabilities due to direct or indirect effects of the disruption.

A small section of the model is shown in Figure 2. This section tracks the movement of afflicted persons into the hospital as emergency and non-emergency patients, their admittance if appropriate, treatment and release. A closer examination reveals linkages to other models (blue and pink variables) such as affliction rate that is generated from the infectious disease model or other disruption model. Treatment rates in the model can also be affected by staffing levels and bed availability [19, 24]. Death rates are coupled with the infectious disease model so that the quality of care can affect the outcomes [25]. A more detailed and complete description of the public health model is available [26].

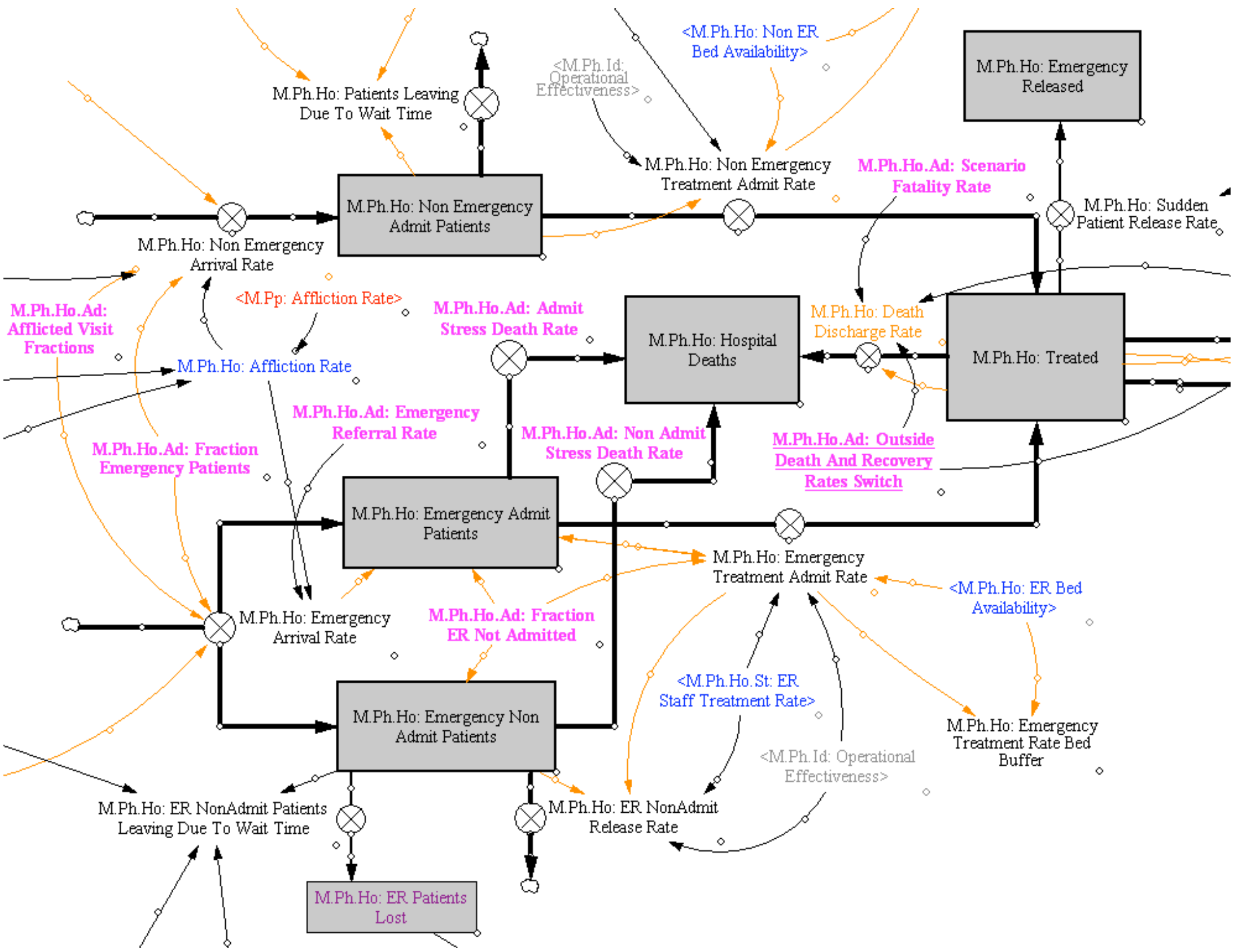
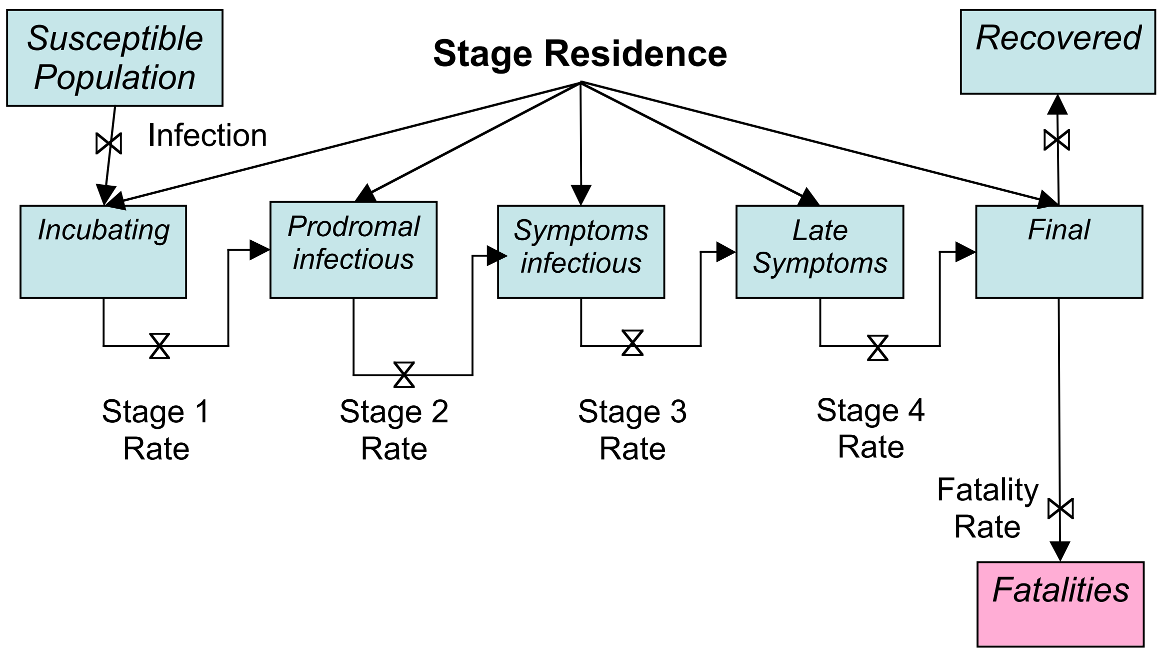


Figure 2: A section of the hospital model in public health

Infectious Disease Model

The infectious disease model is a modified susceptible-exposed-infected-recovered (SEIR) model using an extended set of stages; demographic groupings; an integrated model for vaccination, quarantine, and isolation; and demographic and stage-dependent behavior. As a variant on the SEIR model paradigm, this implementation represents the populations as homogeneous and well mixed, with exponentially distributed residence times in each stage (characterized with a nominal residence time) [27]. However, the use of additional stages and demographic groupings is designed to add additional heterogeneity where it can be useful in capturing key differences between subpopulations for disease spread and response. The stages are represented in a generic manner so that the model can be used for a number of infectious agents by adjusting the input parameters appropriately. This is illustrated in Figure 3.



Error! Bookmark not defined. Figure 3: Infectious Disease Model Stages

The basic reproductive number R_0 is the average number of people infected by a typically infectious individual in an otherwise susceptible population. If the basic reproductive number is greater than one, the disease has the potential to spread. If it is less than one, the disease will die out after only a few generations [28]. The parameters that impact R_0 include the ease of transmission of a disease and the contact rates among the populations. The CIPDSS infectious disease model can either use R_0 as an input into the model or it calculates it as an output of the model.

Government response in the model in the form of quarantine and vaccination programs is initiated after recognition of the first cases in the public health system. The model represents the mitigation strategies for under a variety of policy assumptions. Mitigation options include vaccines (targeted vaccination, mass vaccination, or a combination) [29, 30], antivirals [31, 32], and isolation and quarantine [33, 34]. Vaccination can be biased toward particular subpopulations to model priority vaccinations of children or healthcare personnel. Allowances for refusing vaccination and separating segments of the population who cannot tolerate vaccination out of the queues can also be made. Schools themselves are not included in the generic infectious disease model; but school closing can be modeled by including age-group-dependence for R_0 or contact rates thus allowing age-specific control of the transmission and infections of school-age children.

The model also responds to investments in better hospital care, isolation, and antiviral treatments, which can affect fatality and recovery rates in the population. The model keeps track of the state of the population in terms of immunity, health status, unavailability (sick and/or in quarantine), and fatalities. Unavailability and fatalities are passed to the population and infrastructure models, whose effects can then feed back into the infection model. Examples of this behavior include sickness and fatalities leading to reductions in healthcare staff, which in turn can raise fatality rates in the infection model due to poorer and less timely care.

A portion of the model is shown in Figure 4 where we have focused on the movement of the unexposed population due to infection and a number of different mitigating actions such as contact tracing, vaccination by targeted and mass allocation methods, and similar allocation for antivirals. Not visible in the diagram is the fact that each stock, flow and auxiliary variable is indexed by six demographic groups divided by age with one of these groups corresponding to first responders (medical and emergency response personnel). This sampling of characteristics suggest a variety of factors including mitigating actions and disease and treatment parameters and options that can be exploited in a simulation, allowing the user to explore possible actions and outcomes. The user can affect not only the type of intervention used but the assumptions underlying each of the strategies such as the availability of antivirals or the effectiveness of a vaccine.

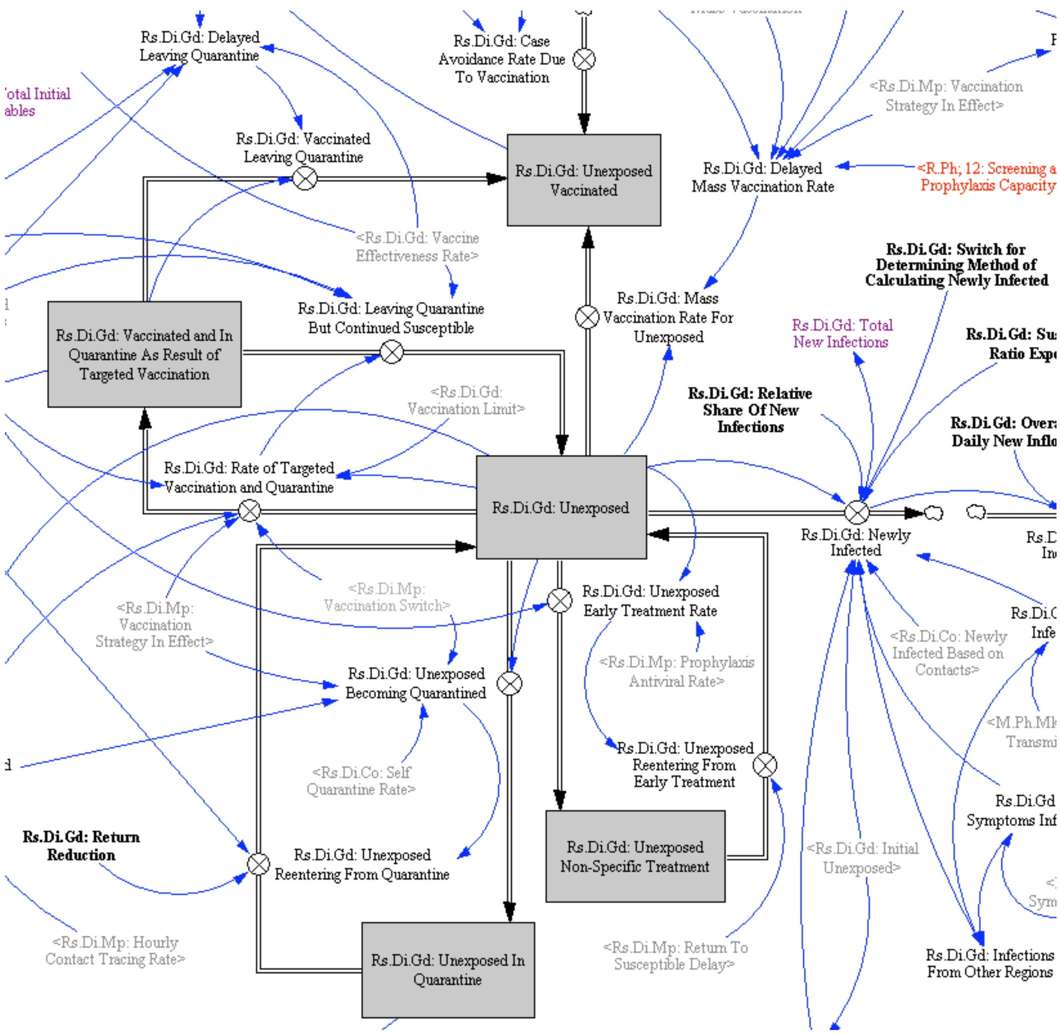


Figure 4: A section of the infectious disease model handling the unexposed population

PROTOTYPE SIMULATOR FEATURE SELECTION

The process of assembling the prototype simulator began by considering potential users and by considering features for the simulator that leverage existing CIPDSS capabilities. This provides value by:

- Deciding who the users might be and the features they will want.
- Speculating on the types of questions the users will ask.
- Developing use cases.
- Completing a prototype to begin getting feedback and validating assumptions about users and features.

At a very high level we considered the following to be of interest:

- A reasonably intuitive interface for setting conditions, running simulations, and examining output
- A pleasing appearance useful in holding the user's interest
- The ability to run scenarios in under a minute up to a few minutes
- Provide access to all key metrics for the scenario and to all key infrastructures
- No familiarity with models, details of scenario, or infrastructures will be required, but will provide extra utility for those having more domain expertise
- Variations of key scenario parameters will be available (e.g., handle multiple diseases)
- Consider providing views into underlying models for some users (although never allow the user to modify the underlying models directly, except through pre-determined inputs)

The next step was to brainstorm on potential users, determine desirable features, and prioritize features for development. The brainstorming group included modelers, managers and an interface expert. All of the ideas were written on Post It notes (a single idea on a single Post It). After the brainstorming session all of the notes were organized into an *affinity diagram* [35]. An affinity diagram is a bottom-up method of organizing brainstormed ideas. The affinity is created by observing what categories naturally fall out of the individual notes rather than starting with predefined categories. The affinity resulted in the following categories: General Features, Analysis, Direction and Reliability. These were further broken down into the following sub-categories:

General Features

- User Input
- Quality of Interaction
- Displaying Results
- Viewing Underlying Models
- Questions

Analysis

- Interdependencies

- Questions the Simulator Should Address
- Scenarios

Directions

- Capabilities
- Users
- Questions

Reliability

- Bullet-Proofing (Verification & Validation)
- Confidence-Building
- Questions

Ideas under each of these topics were collated and redundancies were removed. A sampling of the ideas generated for the prototype simulation is listed below.

General Features: User Input

- Ability for the user to manipulate input parameters
- Limit user's input ranges (min and max values)
- Important classes of parameters: disease characteristics, immediate resources (vaccines, antivirals, antibiotics (cipro), beds, etc.), and delayed resources, e.g., targeted vaccines, production rates, development times for new pharmaceuticals, etc.

General Features: Quality of Interaction

- Provide the user with different levels of detail of the underlying model to aid in understanding
- Provide help files and information displayed as the user hovers over an item
- Develop at least two use cases as tutorials: one for communicable diseases (e.g. smallpox) and one for non-communicable disease (e.g. anthrax)

General Features: Displaying Results

- Adjustable graphs
- To understand behavior multiple outputs are needed
- Organized by subject – for example into disease related, scenario related and infrastructure related items
- Ability to compare outputs from different scenarios (e.g., compare a base case with a user defined case in a tabular or graphical form

General Features: Questions

- Which input parameters should be manipulated?
- How fast do model simulations need to run?
- What visual aids/results do users currently work with when doing this sort of analysis?
- What displays will be most useful in communicating results?
- Multiple results: How are they organized?

Analysis: Questions Simulator should address

- "Net effect" questions, how many people may become ill?
- Do "What Ifs“

- Causal Tracing - "Why are the outcomes so high?" -> find leverage points. Assume that this refers to parameters that are most important which may require sensitivity analysis.
- Which infrastructures are affected and to what degree?
- What do we do about a disease when there is not enough vaccine?
- What should we be doing and investing in now to prepare for an outbreak?
- What "bang for the buck" does a given mitigation strategy provide?

Analysis: Scenarios
- Show relevant disease scenarios
- Show different diseases and how/why different strategies are needed
- Base case scenarios that users can start from and then manipulate the parameters
- Select mitigation strategies, e.g. contact tracing, vaccine, antivirals, quarantine, social distancing, etc.

Direction: Capabilities
- Show capability of modeling approach
- Show integration of infrastructure modeling

Reliability: Bullet-Proofing (Verification & Validation)
- Test extreme values
- Test against other models or analytical solutions

Reliability: Questions
- What types of testing should be done?
- How do we instill confidence in the model results?

Prototype Implementation
- CIPDSS system dynamics models in Vensim1 running underneath
- Sable simulation development environment
- Designed to work with Vensim
- Rapid development possible
- Customizable help system possible
- Views directly into the model possible
- Scripting accessible for customization
- Results animation available
- Graphics import possible in several formats
- Can be run in simulation or gaming modes

Although this process may appear somewhat disorganized we found that numerous features and questions repeatedly came up, allowing the key features of the prototype CIPDSS to coalesce into at least a starting vision for the simulator that, jointly with an effort to become familiar with the Sable interface builder (testing its features), could be transformed into a prototype. This will be our starting point for getting feedback from potential users of the simulation with the intent to producing a simulation environment that will provide value.

PROTOTYPE SIMULATOR

A prototype simulator was built based on available CIPDSS strengths and capabilities, the features of the Sable development environment and the results of the brainstorm and affinity diagram exercise for the simulator interface. The simulator is divided into a series of pages that are easily accessible yet organized so that the user is led to appropriate areas depending on their interest. The main page provides for access to the highest level scenario selection options (disease, severity of event, mitigating actions) and key outputs of the scenario (deaths, economic impact) while providing access to the state of the infrastructures. From here the user is able to navigate elsewhere where they may exercise more detailed control over the scenario and disease or to view the state of and control the operation of various infrastructures.

Main Page

The main page (shown in Figure 5) is organized so that the disease selection and run controls are at the very top with inputs placed generally to the left and outputs to the right. At the bottom is an area termed the 'infrastructure dashboard' where a high-level measure of the stress level in each infrastructure is displayed. These will be discussed in more detail below.

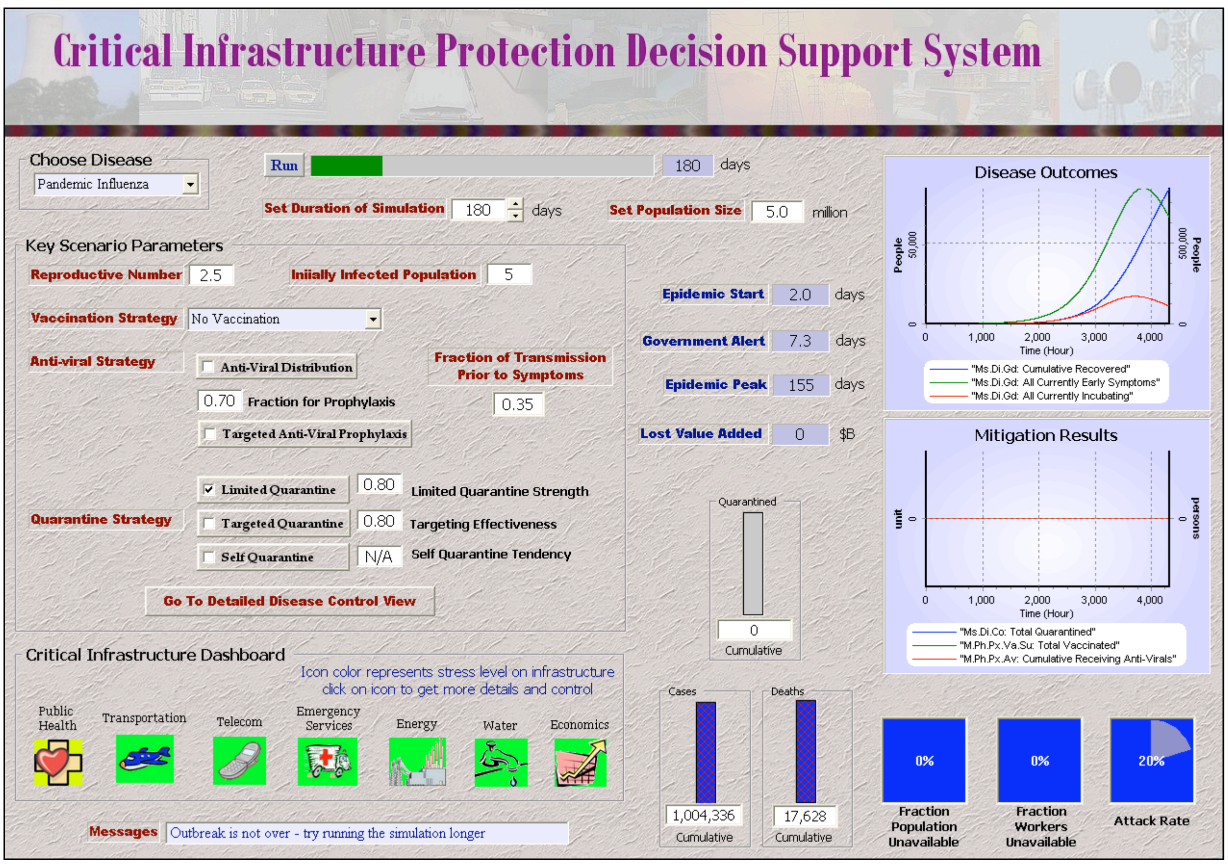


Figure 5: Prototype simulator main view

Figure 6 focuses on the top portion of the main page. The disease of interest is selected from a drop down list which loads a pre-defined .cin file that sets up a default set of parameters (e.g., disease stage time, fatality rates, etc.) that set the appropriate progression of the disease. These parameters can then be over-ridden by the user if desired on this page and elsewhere. The user is able to run the simulation from here and observe the time progression as well as set the duration of the simulation and the population size.

Figure 6: Prototype simulator run control

The next section of the main page, focusing on the user manipulating the highest level scenario controls, is shown in Figure 7. Here the user can decide on a number of mitigation strategies involving vaccination, antiviral treatments and quarantine. Vaccination strategies accessible from a drop down menu include no vaccination, contact tracing only, mass vaccination, targeted vaccination and a policy that starts with targeted vaccination and then switches to mass vaccination after some interval. The user can select the use of antivirals and decide what portion of available supplies will be used for prophylaxis (preventative treatment) and treatment after infection. Quarantine strategies selectable by the user include the use of a limited quarantine for infected individuals, targeted quarantine using contact tracing and an assumption that uninfected individuals will employ fear-based self-quarantine behavior.

This area allows the user to affect some measures of the severity of the disease including reproduction number (the average number of new infecteds created by a single infectious person), the size of the initially infected population, and the fraction of transmissions that occur prior to symptoms being evident in an infected person. Finally a button at the bottom of this area provides access to a separate page giving the user more detailed control over assumptions related to the disease.

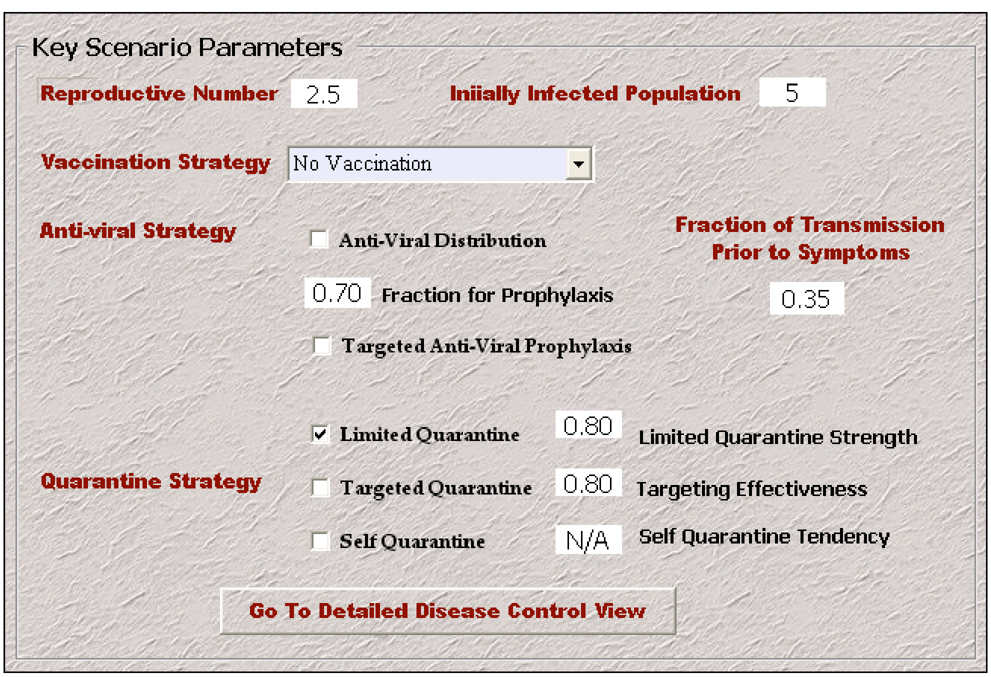


Figure 7: Prototype simulator key scenario controls

On the right side of the main page is high level output from the disease scenario as defined by the user, shown in Figure 8. Graphical output (*Disease Outcomes*) is displayed for incubating, symptomatic and recovered persons as a function of time. A second graph (*Mitigation Results*) displays the result of the mitigation policy such as the total number of persons vaccinated. Timeline information is displayed to the left of the graphs. This includes the starting time of the epidemic, the time of the government public health alert which activates the policies the user has specified, the time of the peak of the epidemic and the end of the epidemic. Infected cases and deaths are displayed using dynamic bar graphs that rise in proportion to the corresponding rates with the cumulative figures displayed below.

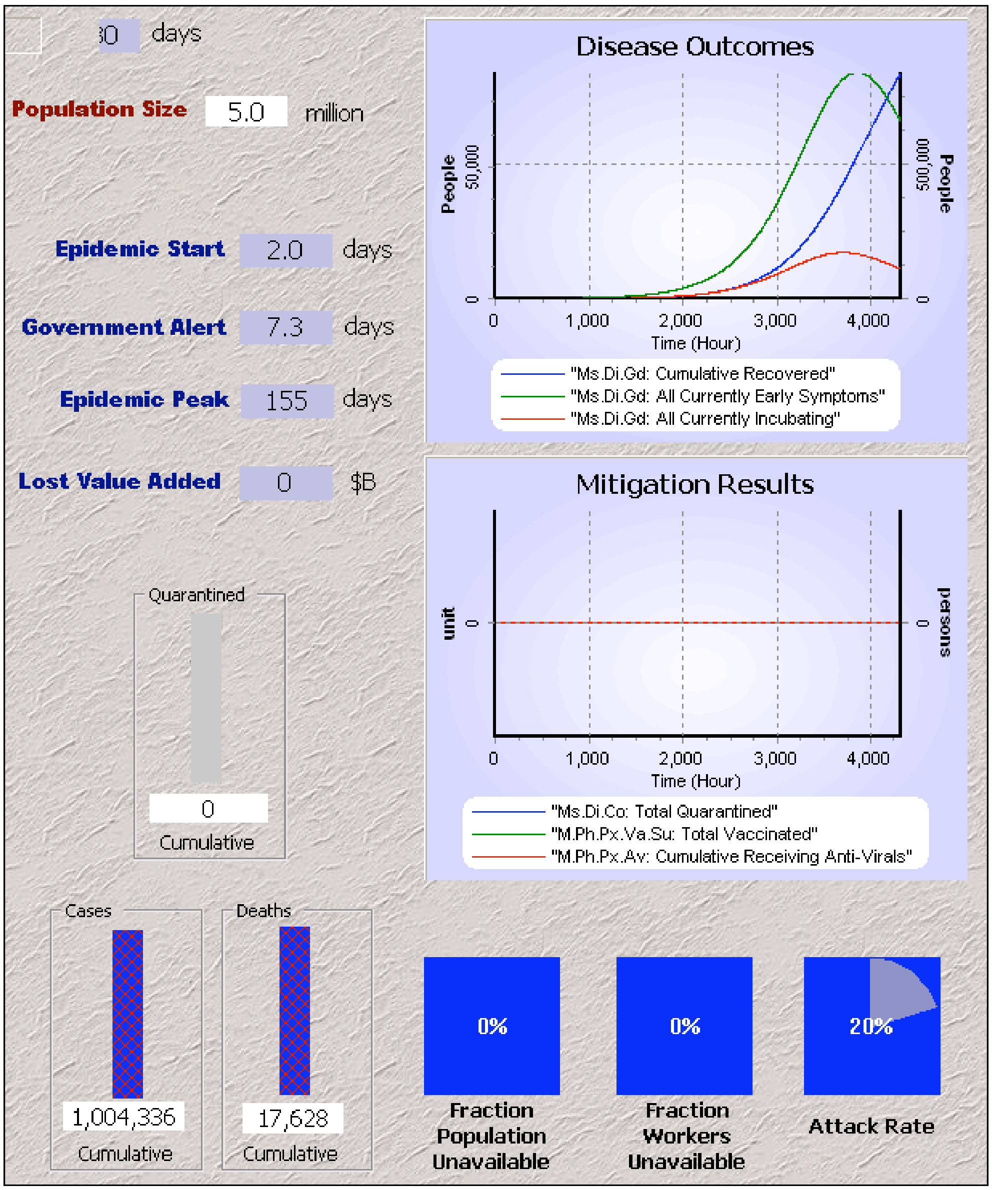


Figure 8: Prototype simulator main page outputs

Finally, a few quantities more amenable to a pie chart type presentation are shown below the graph. These are the attack rate (the cumulative fraction of the population that has become infected over time), the fraction of population unavailable due to deaths, sickness and quarantine, and a similar measure for the working segment of the population.

The final area of the main page (Figure 9) is termed the critical infrastructure dashboard where a general measure of the state of each infrastructure is represented and access to a more detailed view of the infrastructures is provided. An icon representing each of the infrastructures starts with a green background and then turns to yellow as the infrastructure becomes stressed at some level and then turns to red if the infrastructure is at or beyond its limits. These limits are defined within the model based on a combination of measures of infrastructure operation tailored to each infrastructure. For example the public health state is measured on the basis of available beds, available health care staff and available medical supplies. Clicking on the icon takes the user to a page dedicated to that infrastructure for a more detailed look at what is driving the stress level and to exercise more control over the assumptions built into the infrastructure model.

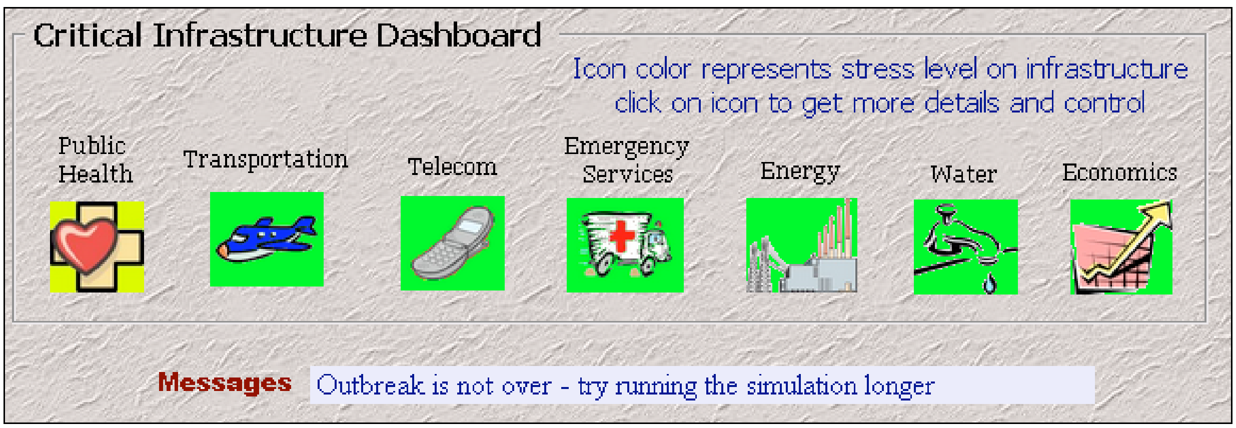


Figure 9: Critical infrastructure dashboard

An example of a page dedicated to an infrastructure is shown in Figure 10 for public health. Note that it is organized similarly to the main page with inputs on the left and outputs on the right. There are navigation buttons in the lower right corner to facilitate the user's movement directly back to the main page or to any of the other infrastructure pages.

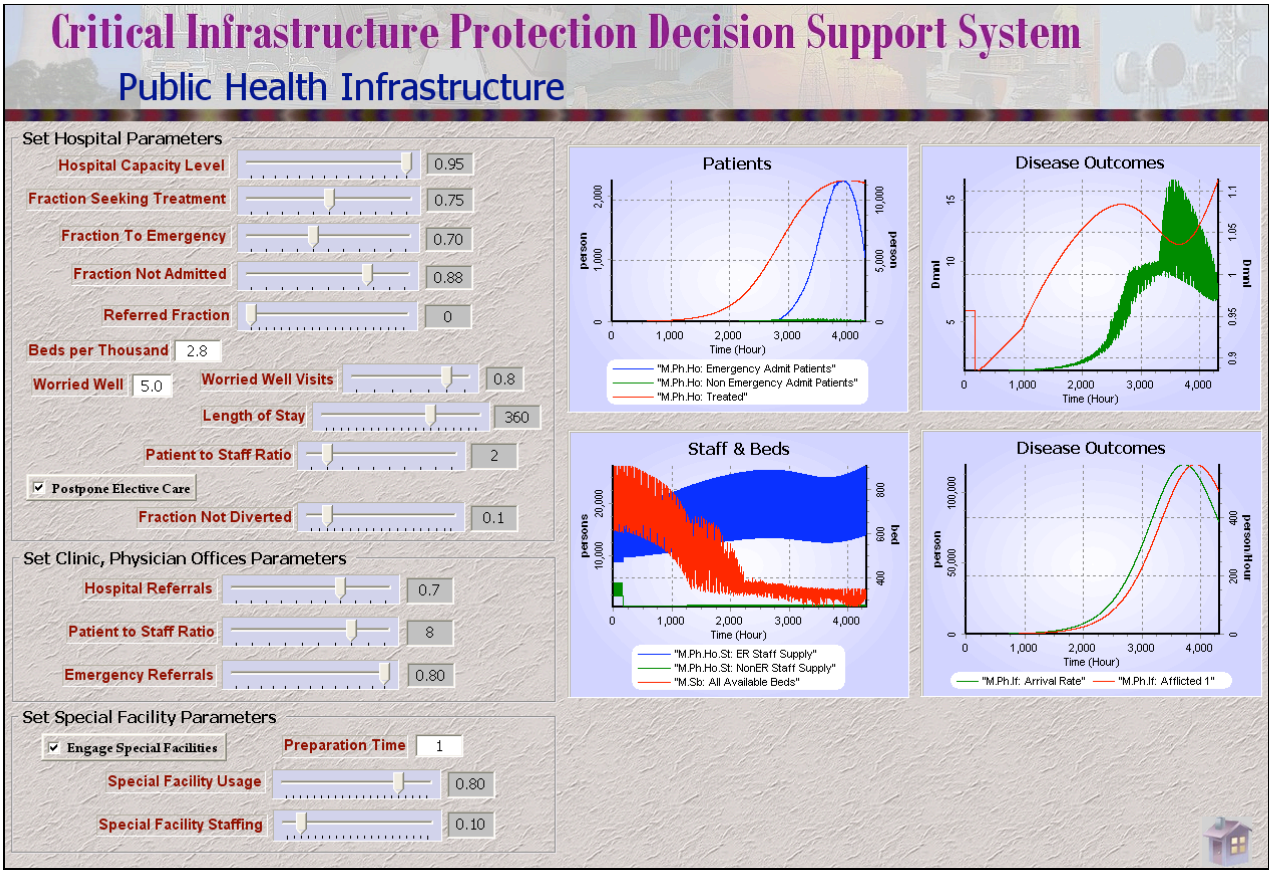


Figure 10: Public health infrastructure page

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