Modeling the Consequences of Major Incidents for Health Care Systems

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Health care systems are complex entities that are difficult enough to operate under normal circumstances. Catastrophes such as natural disasters or terrorist acts can have severe impacts on health care systems by overloading them with casualties. At the same time, these catastrophes can greatly reduce health systems' capacity for dealing with this demand by damaging health care facilities or causing a loss of critical services such as electric power or telecommunications. The consequences of these major incidents are not straightforward and may be transmitted through health care systems in ways that cannot be anticipated.

This paper describes a System Dynamics model that has been used to simulate the effects of major incidents on health care systems. The model can simulate a variety of events from tornadoes or explosions that occur in a short period of time to epidemics that evolve over a number of days. These events can be simulated with or without assuming damage to health facilities and injuries to health personnel. An important use of the model is evaluating various investments that can be made (e.g., backup capacity, stockpiles of pharmaceuticals) that reduce the vulnerability of health care systems to these incidents. The model can be used as a standalone simulator or in connection with models of other critical infrastructures.

Introduction: Need for a System Dynamics Approach in Emergency Planning

The health care system in any area of the United States is a complex enterprise involving many organizations, thousands of employees, and elaborate technology. Components of the system interact with each other in many ways. The area's population depends on the health care system for a wide array of services including some that literally mean the difference between life and death. Health care is an important part of a region's economy and all of the other economic sectors depend on it to keep their workers healthy and productive. An area's health care infrastructure is vulnerable to several types of threats:

- **Direct Attack** Health care has traditionally had a protected status and been "off limits" in military conflicts. Recent terrorist attacks have not distinguished between military and civilian targets and health care facilities cannot be considered exempt from possible attack.

- **Loss of Other Key Infrastructures** Health care and its elaborate technology depend on other critical infrastructures such as electric power and phone systems. Health care is also labor intensive and employees depend on roads and public transportation to get to work. Though there is some provision for backup of electric power and other key services, many health care facilities may not be able to function in a prolonged outage of key services.

- **Sudden, Overwhelming Demand** Health care facilities can also be rendered unavailable for normal services by events that create an overwhelming demand for emergency health care. These events can include natural disasters, transportation accidents, and intentional terrorist acts. The resulting demand can tie up staff and critical facilities such as operating rooms for extended periods of time. Certain events such as epidemics or bio-terror involving contagious infectious agents will create demands that grow over time and present direct threats to health care staff, as was evident in the recent SARS epidemic.

- **Combined Threats** These threats can and are likely to occur in tandem. Natural disasters and other events that produce mass casualties may disable key infrastructures on which health care depends just as the system is faced with an overwhelming demand for its services. A direct attack on a health care facility will reduce the system's capacity and place increased demand on other facilities from both casualties of the attack and the "normal" demand usually handled by the damaged facility.

The direct effects of these threats are complicated and difficult to anticipate. In addition, the complex nature of the health care system will produce indirect, second-order effects that are even more difficult to foresee. Anticipating these indirect effects requires special tools. For example, failure or saturation of some facilities in an area will cause demand to flow to other facilities that may, themselves become overwhelmed. Saturation of certain key services in a hospital such as operating rooms may prolong the stays of many patients in a hospital and increase congestion and crowding. Saturation of rehabilitation

and long-term care facilities may also keep patients waiting in acute care hospitals and also add to congestion. Delays in treating certain acute problems will make them worse and require more intensive care. Delays in treating contagious illnesses will allow them to spread further and require additional treatment resources. Saturation of certain specialized facilities such as burn units may cause spillover into other parts of a hospital that are ill-equipped to deal with this sort of injury.

The focus in planning for bio-terror events and disasters is usually on the casualties of those events. However, prolonged events that include infrastructure outages will produce additional consequences. Half or more of an area's adult population typically has some form of chronic illness that requires ongoing care. A fraction of the chronically ill population develops acute problems that require urgent care on any day. The frequency of these acute problems may actually increase in the presence of a large-scale emergency as a result of anxiety or environmental degradation (e.g., smoke). After a few hours, patients requiring intensive care at home may begin to show up at hospitals if there is no power to run the equipment they depend on. After a few days, patients requiring and not getting treatments such as kidney dialysis will develop acute problems. Patients who run out of medications or forget to take them will also develop problems that require care. If doctors' offices are closed for a prolonged period, people will come to hospital emergency rooms for care.

The complex nature of the health care system, the set of threats it faces, and the potential for these second-order effects as an emergency goes on indicate a need for a System Dynamics simulation model. The effects of these threats cannot be anticipated without such a tool. This paper describes the development and use of a System Dynamics simulation model for this purpose. The model contains:

- the key elements of an area's health care system (hospitals, physicians offices, long-term care facilities),
- its interdependencies with the various other infrastructures, and
- the population it serves including both those people who require care on a regular basis and those who would require care as the result of a particular event such as a disaster or bio-terror attack.

The model is being developed for Sandia National Laboratories which, along with Los Alamos National Laboratories and Argonne National Laboratories is conducting a large infrastructure modeling project for the US Department of Homeland Security. The model described in this paper provides an initial demonstration of concept. It has been used so far to simulate the consequences over time of various individual and combined threats and their indirect effects and potential worst-case scenarios that may result. Results of these simulations are reported later on in the paper.

The paper's final section will describe future work to be done with the model. The model will eventually provide a laboratory for identifying and evaluating different strategies for mitigating or reducing vulnerability to those threats. It will, for example, help to answer questions such as the required capacity of different resources for dealing with particular

threats, the size of regional or national stockpiles of personnel and supplies to support local efforts. The model will also be used in tandem with models of other critical infrastructures developed by the larger effort to understand the far-reaching effects of a major event through an economy.

Health Planning for Emergencies

There is an extensive literature on emergency planning for health care. Much of the literature focuses on bio-terrorism although there is much information on other hazards as well. A web site provided by the University of Maryland is a good guide to many of these sources. (U. of Maryland, 2004) The Joint Commission on the Accreditation of Healthcare Organizations (JCAHO) also has a comprehensive guide on emergency management planning. (JCAHO, 2002) Planning documents from the Metropolitan Washington DC Council of Governments and George Washington University are also rich sources of information. (Metro DC COG, 2001; George Washington University, 2002) Reviewing these sources and others suggests several guidelines for modeling in support of health care emergency management and planning:

- Planning should be done on an "all hazards" basis rather than for individual hazards. Focusing on individual hazards such as bio-terrorism and explosions may lead to plans that are redundant on one hand and yet still leave gaps. (See FEMA, 2001)

- Planning should reflect the demands created by "normal" health care needs as well as those that arise from exceptional events. Some planning documents tend to focus on the victims of mass casualty events without adequately examining how health care facilities will provide for normal urgent needs such as heart attacks and automobile accidents while responding to those events.

- Planning should reflect the entire health care system since its various components are interdependent. For example, physicians' offices and nursing homes and other long-term care facilities may be unable to care for patients in a large-scale disaster that produces major infrastructure failures and may have to send their patients to hospitals, adding to their already overwhelming demand.

- Planning should include all people who are exposed to events, not just those who become ill. There are likely to be opportunities to help contain the number of people who become sick with prophylaxis (e.g., vaccination, antidotes) and other preventive and screening programs if they are applied in time to the larger population that may have been exposed. A study done by the Centers for Disease Control suggests that substantial reductions in the ultimate costs of infectious disease outbreaks are possible with rapid detection and treatment of the potentially exposed population. (Kauffmann et al, 1997).

Modeling of health care emergencies has primarily been limited to single threats such as bio-terrorism. A good example is the Weill-Cornell model that uses a spreadsheet to determine the capacity required to treat victims of a bio-terror incident (Hupert, 2003).

Overview of the Model--Health Care, The Population, and Other Infrastructures

Figures 1 and 2 suggest how the health care sector, population, and the other infrastructures might fit together. In Figure 1, the population is divided (initially) into a healthy, functional population that is able to work and a non-functional population that requires health care. Some of these health care needs are a "normal" result of chronic illnesses and accidents while others may be the result of a mass casualty event. Health care and emergency services workers may be disabled by such an event, especially if they are running toward it while others are fleeing. A recent study by the Government Accounting Office (GAO) suggests that many emergency services and health care workers are not adequately equipped with and trained to use personal protective equipment that would keep them safe in an event such as an accidental or intentional chemical release. (GAO, 2003) Workers from other infrastructures may also be disabled just as part of the general population or because of particular risks (e.g., electrical linemen out in a storm). The model makes it possible to vary assumptions about the fractions of different sub-populations exposed to and disabled by an event.

The capacity of the health care sector to deliver services is dependent on the number of workers it has available as well as the availability of services from other critical infrastructures such as electric power, telecommunications, and water and sewage treatment. Damage to the transportation infrastructure may also affect the ability of health care workers to get to work. An Emergency Management Guide prepared by the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) suggests that other staff needs such as the provision of alternative day care arrangements are also essential guaranteeing availability of staff. (JCAHO, 2002) Health care facilities can also be damaged directly by a natural disaster or bomb or contaminated by patients who have been exposed to toxic chemicals or organisms.

Figure 1 indicates that the demand for health care and capacity to provide it determine the backlogs that build up over time, especially in response to a mass casualty event, and the time required to provide treatment to patients. The resulting timeliness, effectiveness, and patient throughput determine how rapidly patients who are temporarily disabled can go back to work and how large a fraction of those affected by an event die or become permanently disabled. The diagram also indicates that outside resources available through various Federal programs can help to augment local capacity or otherwise meet health care needs (e.g., flying patients to other regions as part of the National Disaster Medical System (NDMS)). These outside resources appear in red on this diagram and on the other diagrams in this paper.

Figure 1 suggests a set of large feedback loops in which timely provision of health care can help to restore a larger fraction of the working population. Restoration of the working population helps to maintain health care and other critical services on which health care depends and enables the health care sector to continue functioning effectively. These loops can, of course, work in the opposite direction and cause widespread paralysis. Losses of health care workers, for example, can keep the health care system from functioning effectively and from restoring those workers and others to working status.
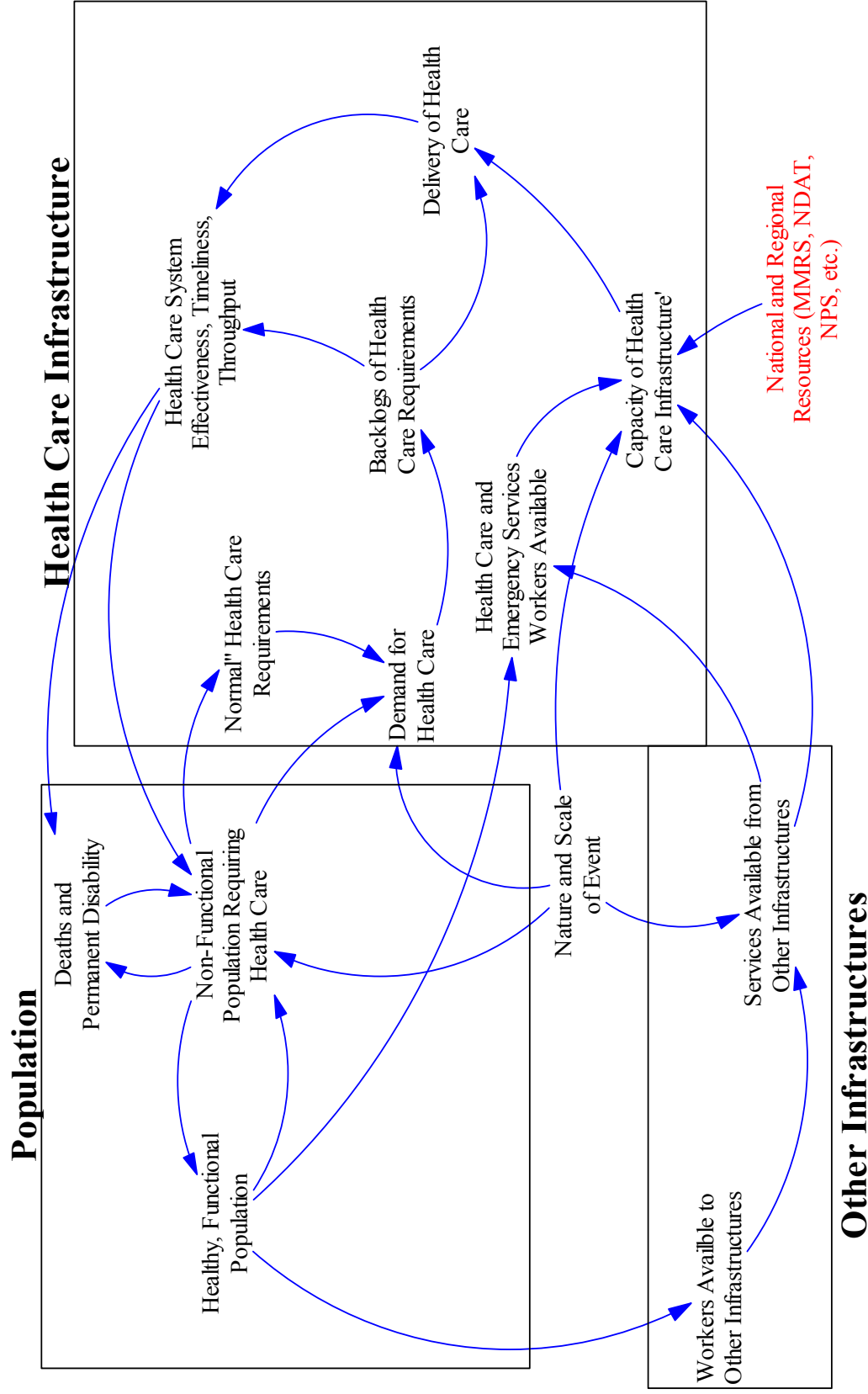
Figure 1: High-Level Overview of Health Care Infrastructure in Relation to Population and Other Infrastructures

Figure 2 goes into more detail about some of these relationships, but still at an overview level. It indicates that the population structure is replicated several times to segment the population into such categories as the working population (divided into health care and emergency services and all other infrastructures), non-working 18-65, under 18, and over 65. Figure 2 also suggests that certain strategies for mitigation and prevention (e.g., vaccinating a population early in an outbreak of a contagious disease) can reduce disability and requirements for health care. It indicates that, in addition to the segment of the population that becomes sick as the result of an event, there will be many others who may have been exposed. They need to be screened in order to rule out illness, allay their fears, and render them fit for work.

The diagram also describes at a high level the flow structure within the health care system in which patients initially present at doctors' offices and clinics and hospital ER's. Many can be treated and sent home, but others will have to be treated as inpatients in the hospital. A lack of sufficient bed capacity in a mass casualty event may create a bottleneck in which an ER becomes overloaded because there are no beds in which to put patients who need to be admitted. Patients who cannot get care at their doctors' offices (possibly as a result of a widespread prolonged power failure) and go to the ER instead may also swamp ER's. Delays created by these bottlenecks and backups can reduce the effectiveness of health care and increase the length of time people remain disabled and the fractions that become permanently disabled or die.

The health care emergency preparedness literature discusses the concept of "surge" capacity in which areas such as cafeterias and non-clinical personnel are used for patient care and in which patients are redistributed to facilities that have unused beds. A study done by a group at George Washington University contains an especially good review of the methods available to increase the nominal capacity of health care systems. (George Washington University, 2002) These include advance credentialling of volunteers with some health care experience (e.g., retired nurses).

Representing the Population

Figure 2 showed an aggregate view of how an area's population might be represented. Figure 3 goes into more detail in depicting a module that is replicated multiple times to represent different segments of the population. As indicated, a set of five sub-populations includes the working population further segmented by those working in health care and emergency services and those working in all other infrastructures, the non-working population ages 18-65, those under 18 and those over 65. The majority of the population starts in the fully functional category although some, especially in the over 65 group, might start in normal circumstances in the category that is disabled and already requires significant health services.

The nature and scale of an event would determine a population affected in some way (e.g., chemical release carried by winds over a 25 square mile area, people potentially exposed to an infectious disease). This population could be quite large and include people who do not ultimately become sick, but might need screening and prophylaxis (e.g., vaccination) to reduce the number of people who ultimately do become sick.
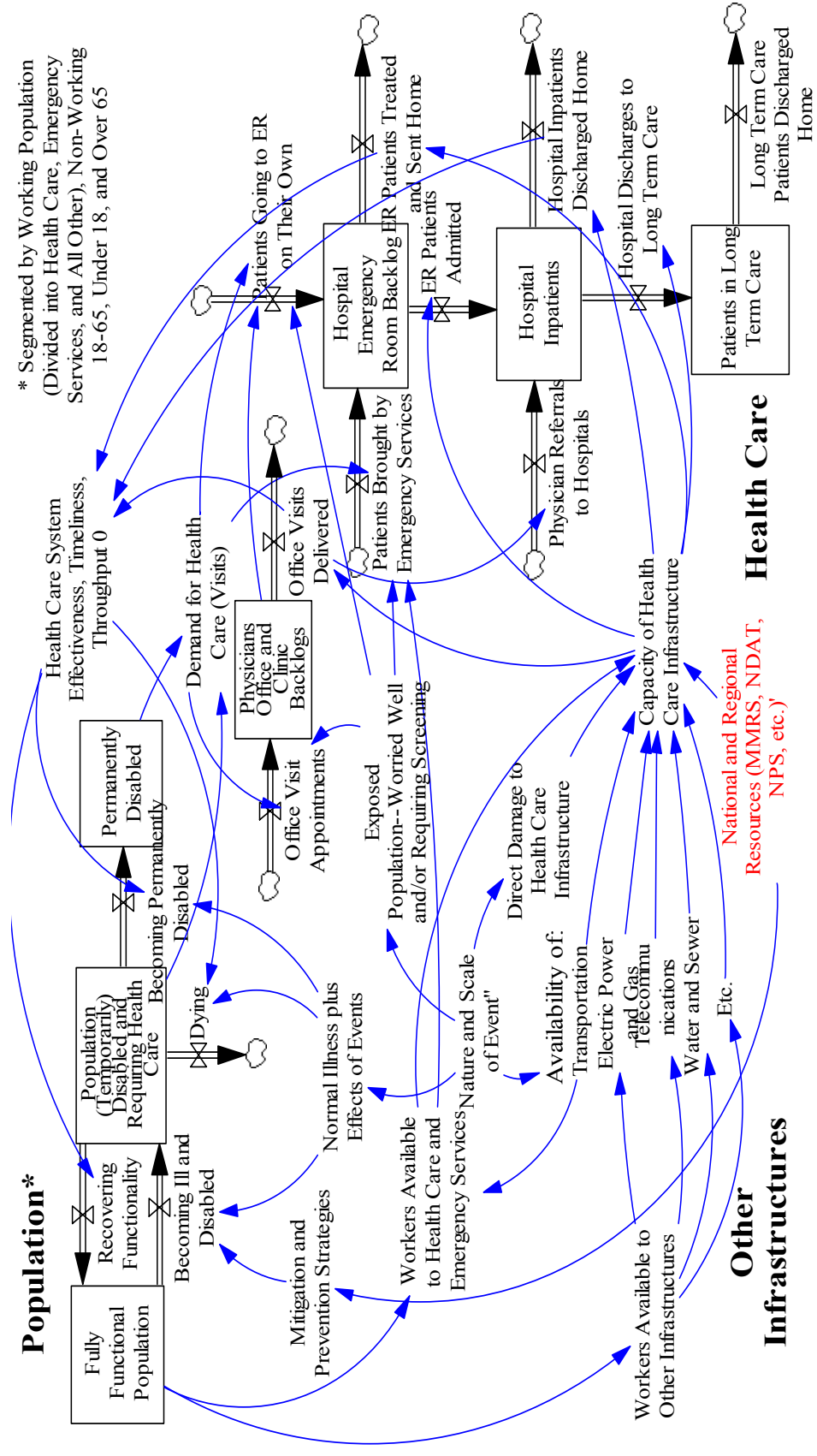
Figure 2: More Detailed Overview of Health Care Infrastructure in Relation to Population and Other Infrastructures

Many people, once exposed, may not be able to return to work until they have been cleared by some sort of laboratory test or medical examination or been vaccinated or otherwise protected. Some fraction of those exposed will not become ill and can, after a time, be considered part of the fully functional population. Even though these people do not eventually become ill, they must be included in screening and prophylaxis programs.

Some fraction of the people who are exposed will become disabled and require medical care. The pattern in which they become ill will vary over time from almost instantaneous in the case of an explosion to over several days for an infectious biological agent to much longer in the case of a radiological release. Even something seemingly instantaneous such as an explosion can have delayed effects in a condition referred to as "blast lung". Some of the people who become ill will die immediately or after some time. All will require various amounts of health care that may restore them to fully functional status fairly quickly if they have only minor injuries. Others may be treated successfully, but because of the nature of their injuries, remain temporarily disabled and not able to work for a period of time. Some will die during the course of medical treatment. Others will become permanently disabled as a result of their injuries and continue to require substantial amounts of medical care. Some will die after a prolonged period of disability. People with illness or injuries resulting from an event add to the normal demand for health care (e.g., due to heart attacks, motor vehicle accidents) that continues during a major emergency and may increase as a result of the stresses created by such an event.

Even in the absence of an event that produces injuries, some people may require health care on an emergency basis as a result of widespread infrastructure breakdown. These would include disabled people normally able to live at home with supportive devices, but who must be hospitalized if widespread power failures make those devices inoperable. (Hospitals typically have backup power.) A larger group of people may develop acute health problems if a there is a widespread disruption in the pharmaceutical supply chain and people with chronic illnesses such as diabetes cannot get medications they need to keep their conditions under control.

The stocks and flows shown in Figure 3 are important drivers for other parts of the model. The size of and reductions in the fully functional population will determine the availability of people to work in health care and emergency services as well as in other infrastructures. Those exposed to an event will determine the requirements for prophylaxis and screening programs as well as the numbers of people who will become sick over the succeeding hours and days. Those disabled and requiring medical care, both for normal needs and those resulting from an event, will determine the demand for health care. The effects on the population also provide a set of measures for comparing a number of scenarios. These measures include mortality rates and life-years lost, disability days and fraction of the population becoming permanently disabled, health care costs, and total costs computed by assigning costs to lives and disability days. The CDC study cited earlier provides such estimates for a number of scenarios using cost equivalencies taken from other studies. (Kauffmann et al, 1997).
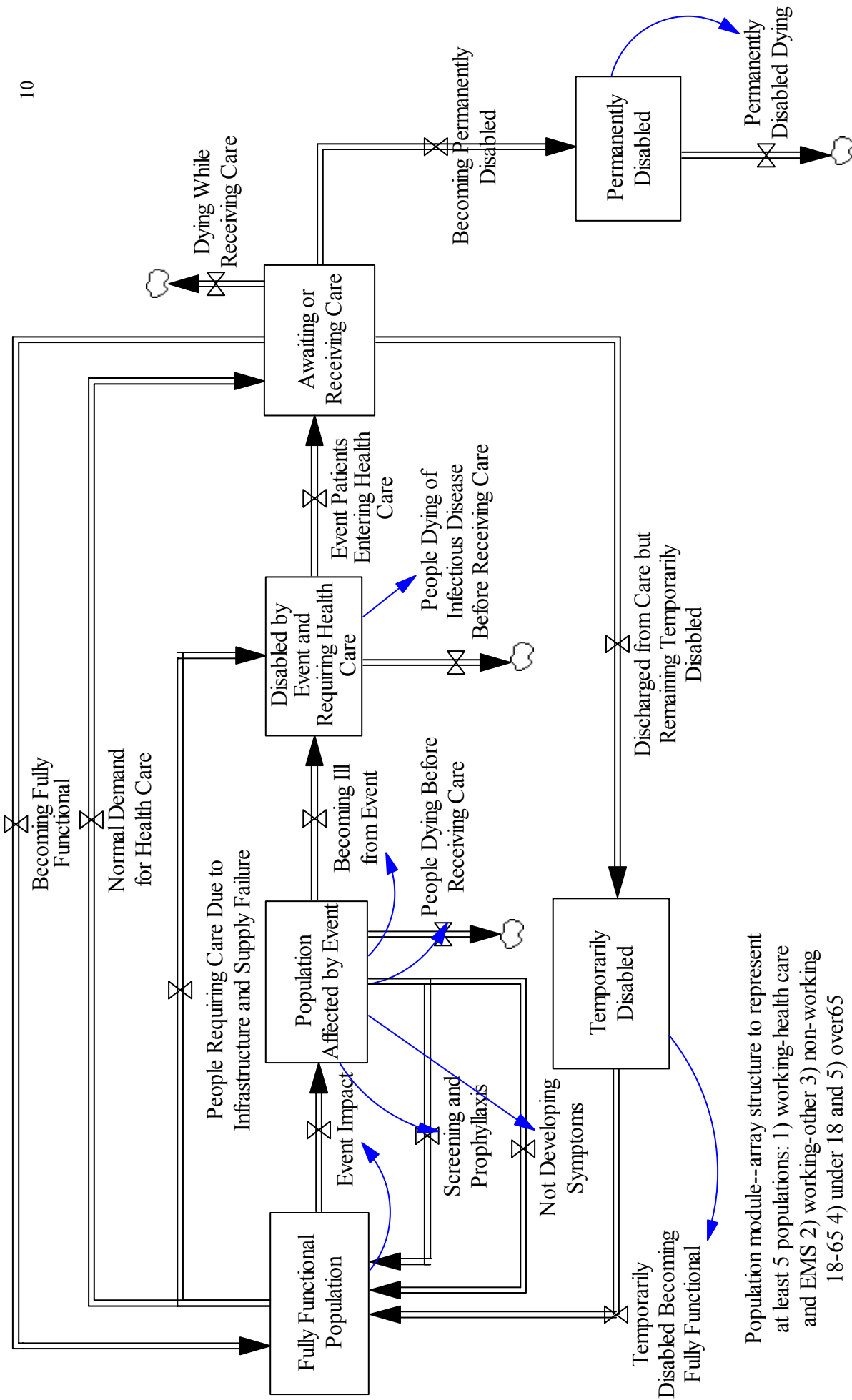
Figure 3: Population Module

Caring for Sick or Injured Patients

As suggested in Figure 2, the model contains a detailed structure for capturing the flow of people who become sick or injured as a result of an event. Figure 4 shows part of this structure related to patients coming to Emergency Rooms in hospitals, either on their own or via ambulances operated by various emergency services. As with the population flows shown in Figure 3, this structure is replicated for each of the population subgroups using Vensim's array capabilities. The fraction coming by either route depends on normal patterns and on those that might prevail in a mass casualty event such as an overload on the emergency services. Such an overload might cause even severely injured patients to be brought directly to the hospital by private automobile, bypassing the emergency services entirely. Some fraction of the patients treated in the field by emergency services will die before reaching the hospital, others will have relatively minor injuries and be sent home without going to the hospital, and some will be brought to the Emergency Room for treatment.

The majority of patients will go directly to the Emergency Room by private automobile. The numbers going to the Emergency Room will, of course, increase greatly in a mass casualty event. Adding to this number will be patients who may not be severely ill, but cannot get care at their own physicians offices and clinics because they are overloaded or perhaps are shut down due to a natural disaster. The fraction of patients dying during treatment in the ER depends on the average severity of injury and illness resulting from the event and the average delay before people receive definitive care. The majority of patients treated in the ER will be sent home, but some fraction will require admission to the hospital as inpatients. The fraction requiring admission will also depend on the average severity of patients' illnesses and injuries. The time that patients remain in the ER will be a function of the volume of patients seeking care and the capacity of the ER to treat patients. Losses of capacity may result from some of the hospitals own staff becoming disabled or widespread infrastructure failures that reduce the hospital's access to electric power or telecommunications.

Figure 5 shows the more detailed set of relationships that affect the flow of patients into and through inpatient hospital beds. As with the other sectors, the flow is governed by both potential demands, the volume of patients coming from "upstream" components of the health care system, and the capacity to deliver care. Patients may be admitted from the hospital's own emergency room or be referred by doctors' offices and clinics. Some hospitals in an area may also have to accommodate patients from other hospitals that have closed or reduced their services. Most patients are discharged home, but a small fraction requires long term care in nursing homes or rehabilitation hospitals. A lack of available long-term care beds will keep patients in the hospital longer. An event that causes long term care facilities to shut down will therefore have an indirect effect on hospitals, especially if the hospitals must take some of the more severely ill long term care patients. Some fraction of the patients in the hospital will die during their stay. The fractions dying and becoming permanently disabled will depend on both the treatment they are able to get in the hospital and the timeliness and effectiveness of treatment received earlier on the way to the hospital and in the ER.

The hospital's inpatient capacity is affected by the availability of staff, pharmaceuticals and other supplies, and support from other infrastructures such as energy. Damage to patient units or chemical or biological contamination can also reduce capacity. Capacity affects both the number of patients who can be accommodated in beds and the length of time it takes to complete their stay which, in turn, affects the number of patients who can be treated as inpatients over time. The length of stay is, in turn, affected by the volume of care that can be provided by the hospital's diagnostic and treatment services such as its operating and recovery rooms and radiology and laboratory services. If these services are operating at only a fraction of their normal capacity, because there are a limited number of staff or a lack of electric power, it will take longer to serve patients and discharge them from the hospital.

There are several ways in which outside help can increase the availability of hospital inpatient services, highlighted in red in Figure 5. Arrangements through the National Disaster Medical System and Metropolitan Medical Response System can help to accommodate some patients in out-of-area hospitals. Supplies provided by the National Pharmaceutical Stockpile and arrangements with vendors can help to keep a lack of medications from being a constraint on care delivery. Staff provided through National Disaster Assistance Teams and other mechanisms can also augment capacity.

The hospital emergency preparedness literature discusses the concept of "surge" capacity in which certain adjustments can be made to increase the number of patients treated in a mass casualty event. (American Hospital Association, 2000) These are shown in italics in Figure 5. One approach, already mentioned, is to send some patients to other hospitals. Another is to quickly evaluate patients in the hospital and discharge those who are less severely ill and to defer the admissions of elective patients whose surgeries can be put off until after the event is over and the hospital has recovered. The downside of getting rid of patients who are less severely ill is that the average severity of patients who are admitted to and remain in the hospital is greater and the needs they have for care are also greater.

Credentialling and training standby staff in advance can also help meet additional demands. Having materials on hand to effect rapid repairs may also allow a hospital to bring damaged units on line more quickly. The literature also refers to the concept of "engineered failure" in which everyday standards are gradually relaxed in an emergency (while still maintaining patient safety) rather than having the system fail completely and catastrophically. Simulations with the model will help to indicate the extent to which sources of outside assistance and surge capacity can help an area's hospitals function during an emergency and meet the exceptional demands that are presented.

Capacity in this model reflects aggregate hospital bed capacity for a geographical area. How much of that capacity is available for responding to mass casualty events depends very much on the quality of systems of coordination that are set up to distribute patients among facilities with available beds and services. The literature suggests that poor coordination has reduced effective bed and service availability in a number of mass casualty events.
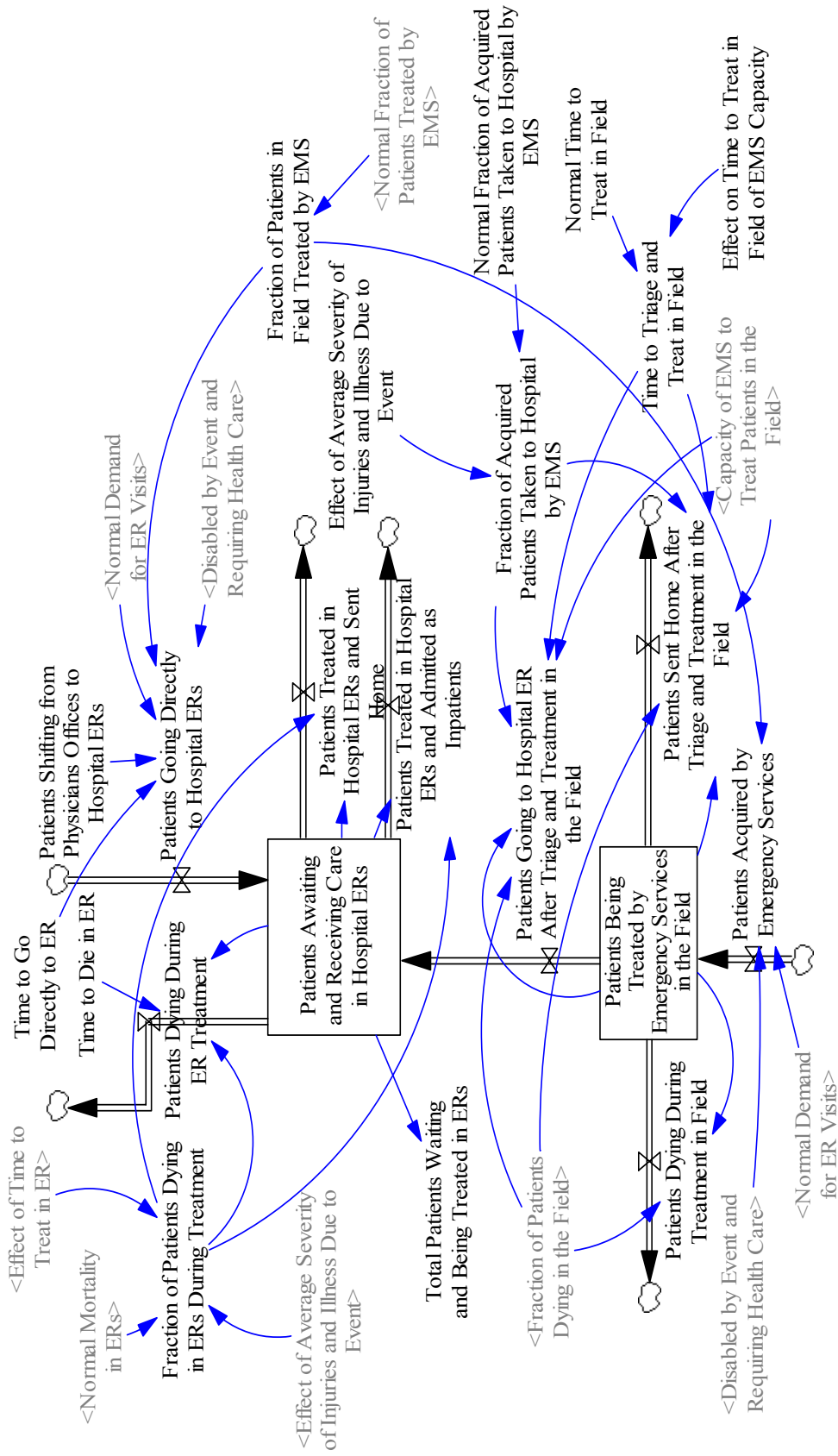
Figure 4: Detailed Structure Involving Flow of Patients to Hospital Emergency Rooms
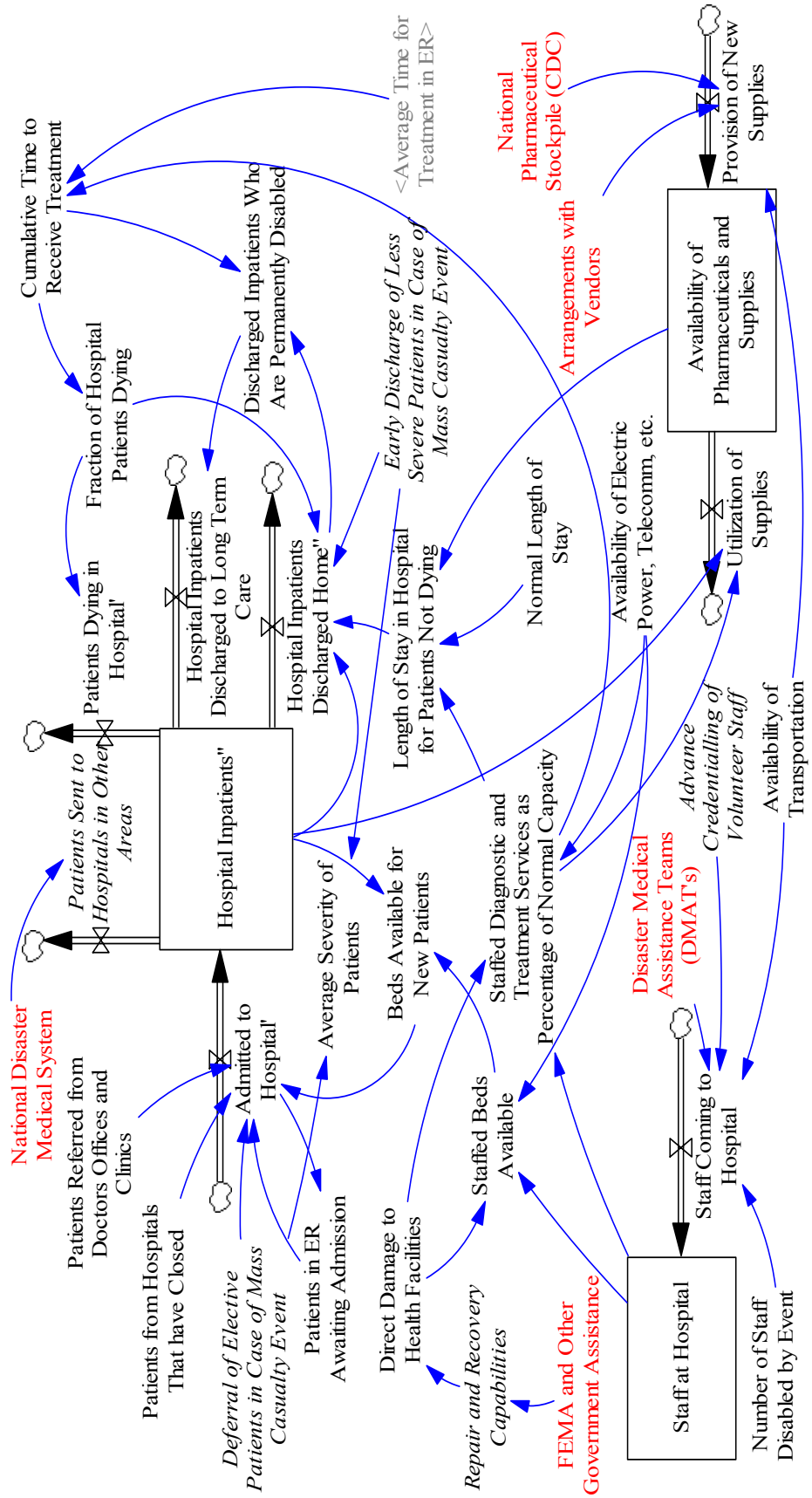
**Figure 5: Factors Affecting Inpatient Hospital Care**

Simulating Events with the Model

The model can simulate several types of events to help decision makers understand the impact of these events on health care systems:
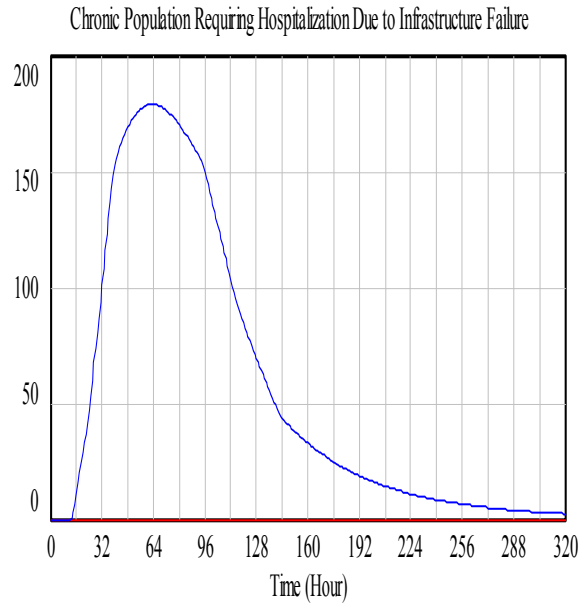
- **Widespread Infrastructure Failures** in which there are no immediate injuries, but a loss of critical services such as electric power and telecommunications. These events may also include failures of transportation systems that keep health care workers from getting to work or pharmaceutical supplies from being shipped around the country. These failures will have their principal effect by reducing the capacity of the health care system to handle normal demand and secondary effects such as requiring emergency care for seriously disabled people who can no longer be cared for at home.

- **Limited Duration events** such as an explosion, sudden storm (e.g., tornado), earthquake or other event that does all or most of its damage and injures or makes people sick in a limited amount of time. Users can specify the fraction of the population affected and duration of the event. Default values can be used for parameters such as the fraction of people exposed who die before getting care or they can be changed to reflect assumptions about a particular event.

- **Introduction and Spread of a Pathogen, Toxin, Poison, or Radioactive material in a way that causes people to become ill over a number of days or longer.** This can occur by
  - Natural means such as the spread of a virulent form of influenza
  - Intentional introduction of the pathogen or other substance in
    - A pulse such as airborne release, explosive device, etc. or
    - More gradual manner such as in the food or water supply
  In the case of a pathogen that produces an infectious disease, the user can also choose to whether to simulate a contagious disease that can be spread person-to-person once introduced into the population or one that does not spread.

- **Combined Events** in which, for example, might include an event such as an earthquake that produces a number of injuries and also disables much of the infrastructure on which the health care system depends.

1. Widespread Infrastructure Failure

Figure 6 shows a series of results for a set of events in which a health care system is forced to deal with a widespread failure of critical infrastructures. An event resulting in 80% loss of capacity by health care facilities during the first day is followed by gradual recovery over the rest of the two-week period. There is also a 50% loss of capacity in the transportation system that keeps health care workers from getting to their jobs and loss in the ability to bring pharmaceuticals into the region and to manufacture those goods within the region. The blue lines represent the results of this simulation vs. baseline values shown in red. This and the other simulations assume a region with 100,000 people and health care resources and other characteristics typical of the US population.

Total Emergency Patients Awaiting Admission
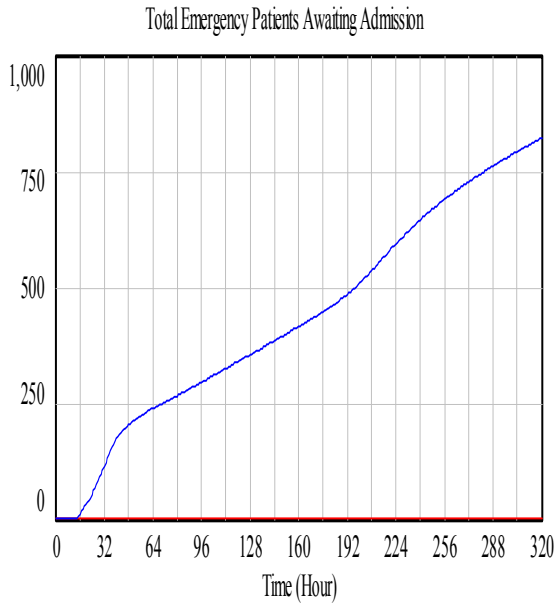
Total Emergency Patients Awaiting Admission : infra break ───────
Total Emergency Patients Awaiting Admission : base ───────

Emergency Patients Awaiting
Admission to the Hospital

Chronic Population Requiring Hospitalization Due to Infrastructure Failure

Chronic Population Requiring Hospitalization Due to Infrastructure Failure[over65] : infra br
Chronic Population Requiring Hospitalization Due to Infrastructure Failure[over65] : base

Chronic Population Requiring Hospital
Care Due to Infrastructure Failure

Total Fully Functional Population
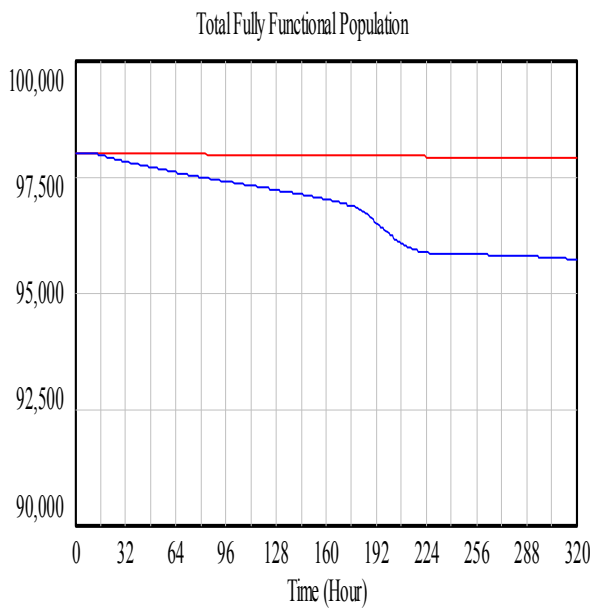
Total Fully Functional Population : infra break ───────
Total Fully Functional Population : base ───────

Fully Functional Population

Total Cumulative Deaths
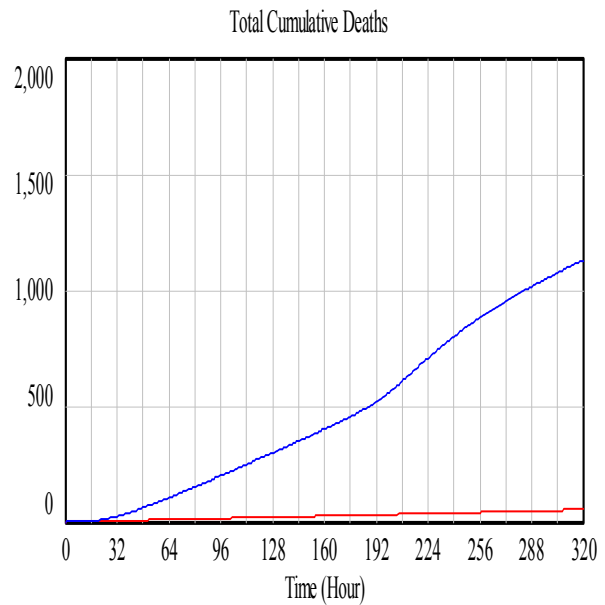
Total Cumulative Deaths : infra break ─────── People
Total Cumulative Deaths : base ─────── People

Total Cumulative Deaths

**Figure 6: Impacts of Infrastructure
Breakdown (Blue) vs. Baseline (Red)**

The backlog of patients awaiting emergency admission to hospitals is the most dramatic indicator of what would happen. The sharp growth in this backlog of patients waiting to be admitted is the result of two things. One is simply the piling up of normal demand for emergency admissions that cannot be accommodated. The other is the sudden need for hospitalization by severely disabled (primarily elderly) people who cannot be cared for at home because of the lack of electric power and other services. The number of these people requiring hospitalization is shown in the second graph. They are able to go home as services are gradually restored. However, there is a second "growth spurt" of demand for hospital care as widespread problems with transportation and the pharmaceutical supply chain lower the availability of drugs required by people with chronic illnesses. These people begin to seek medical care and many require hospitalization because they are not getting the proper medications. The fully functioning population declines in two stages as many people are forced to wait for care or are temporarily disabled after receiving care. The other important consequence is that the long delays in receiving care cause people to become more seriously ill and the cumulative mortality rate is significantly greater than it would have been without the infrastructure breakdown.

These results are helpful on several levels. For one, the size of the backlog of emergency patients awaiting admission in a typical region such as this one can suggest the level of backup resources that might be required. The additional beds could come from arrangements with nearby regions whose infrastructures are unaffected or with self-contained field hospitals that can be flown into a region and set up on short notice. Figure 7 shows how the availability of a 200-bed field hospital would reduce the size of this backlog (blue line). (A field hospital would have to be totally self-contained and staffed since it could not draw on the region's crippled infrastructure.) Another potential value of these simulations would be to provide cost projections that can be used in cost-benefit analyses of various infrastructure protection measures.
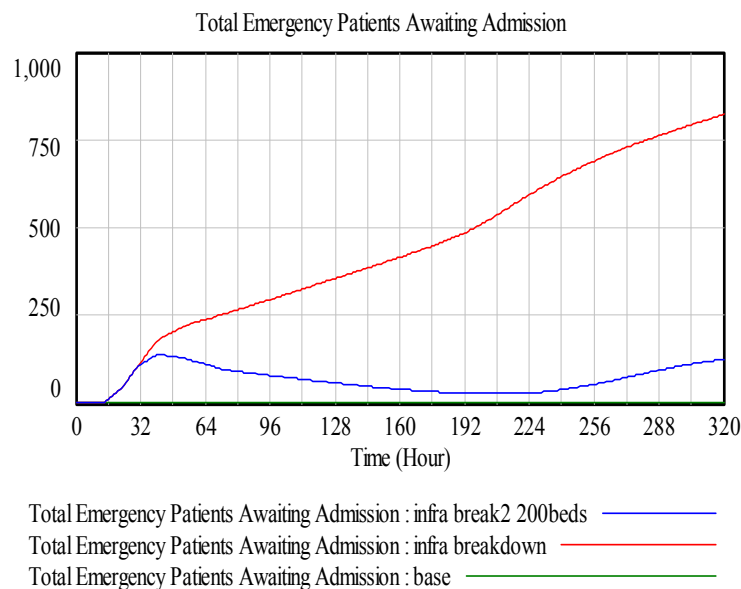
Figure 7: Effects of Making 200 Additional Beds Available (Blue) on Backlog of Patients Awaiting Admission in vs. Extreme Infrastructure Failure Alone (Red)

2. Limited Duration Events

The next set of simulation results shows the impact of a limited duration event. An event such as a large explosion occurs at a public gathering and affects 2,000 people or two percent of the region's population. 20% are close to the blast and die immediately or soon after. The remainder of those affected are distributed evenly between those who are further from the blast and have minor injuries that can be treated in doctors offices and clinics and those who are more seriously injured and require care from a hospital's emergency room. The majority of those treated in the emergency room are sent home after treatment, but some require hospitalization as inpatients. Figure 8 shows the effects of this type of event on the population and health care system (blue lines).

Many deaths occur almost immediately among those closest to the explosion. Additional deaths occur in the succeeding hours as people die during treatment. The number of people awaiting care in hospital ER's peaks a few hours after the event at around 500. Even though only a fraction of the people treated at the ER require admission, there are up to 40 people waiting many hours to days for an inpatient bed to open up. The fully functional population drops initially as people are injured and require care and then recovers as people are treated and are able to go back to work and other activities.

What if the same number of people are affected, but are more severely injured on average, perhaps because the crowd is more densely packed and they are closer to the explosion when it occurs? Figure 9 shows the effects of assuming more severe injuries on average (blue lines, event with "normal severity in red). The number of people waiting for inpatient beds, at its peak is considerably larger, reaching about 125 compared to 40 in the simulation with less severe injuries. Much of the reason for this larger peak is that people admitted to the hospital with more serious injuries have to remain there longer, as shown in the second graph in Figure 9.

3. Introduction of a Pathogen

The next set of simulations deals with the introduction of a pathogen to which the same 2,000 people are initially exposed, perhaps through an airborne release at the same type of public event. Figure 10 shows a set of graphs for this sort of event in which the results are compared to those for the 2,000-casualty explosion or similar type of short-duration event. In this simulation, we assume that the pathogen causes those exposed to become ill, but that the disease is not contagious and they won't spread it to anyone else.

Deaths occur more gradually when the pathogen is introduced (blue lines) than in the short-duration event (red lines) since it takes several days for symptoms to develop and people to get sick enough to die. Peaks in health care system workload come later for the same reason. The peak for people seeking care in emergency rooms is lower than in the short-duration event affecting the same number of people, but the number waiting for care persists much longer as people continue getting sick long after the release takes place. For the same reason, the number awaiting admission peaks later, but at a much higher level than for the short-duration event as new people getting sick "pile on" and add to the number of people waiting for a bed.
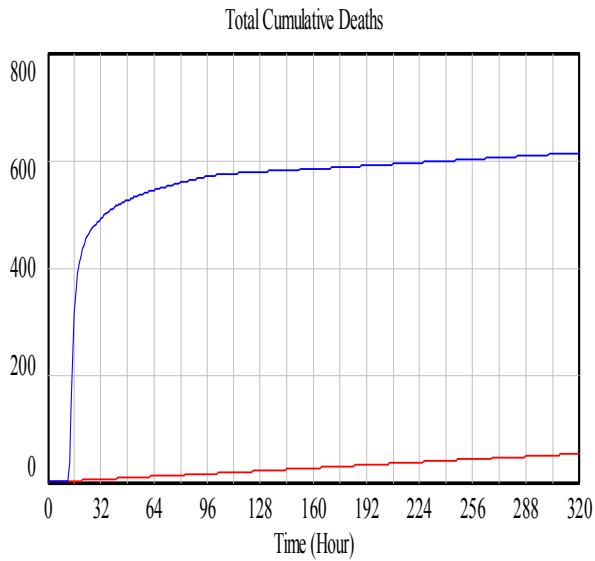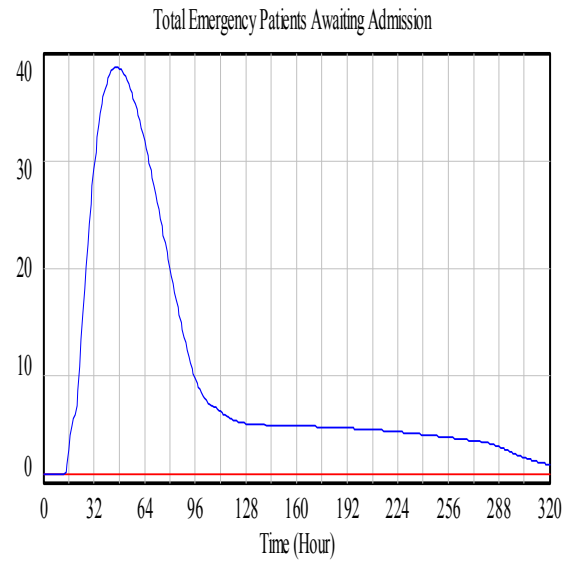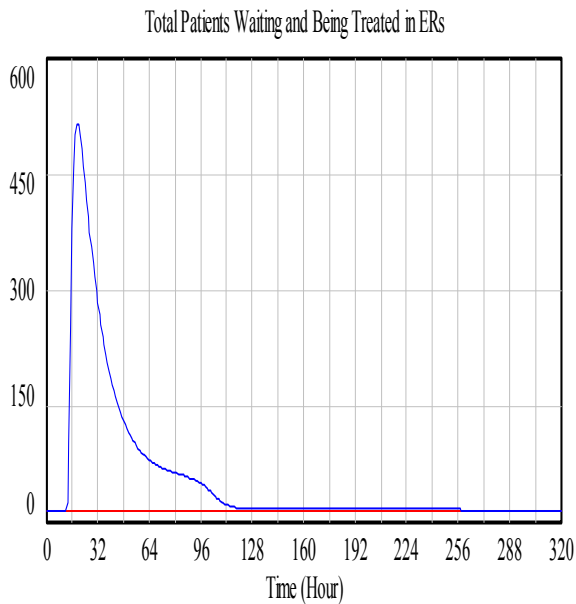
Total Cumulative Deaths

Total Emergency Patients Awaiting
Hospital Admission

Total Patients Waiting and Being
Treated in ERs

Total Fully Functional Population

**Figure 8: Results of a 2,000 Casualty
Event (Blue) vs. Baseline (Red)**

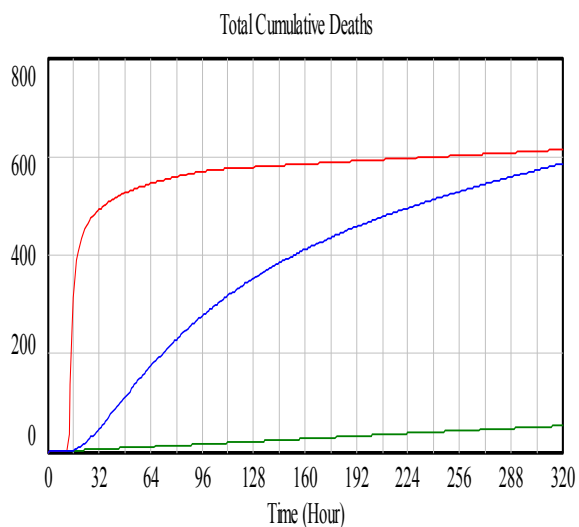Total Emergency Patients Awaiting Admission

Average Inpatient Length of Stay
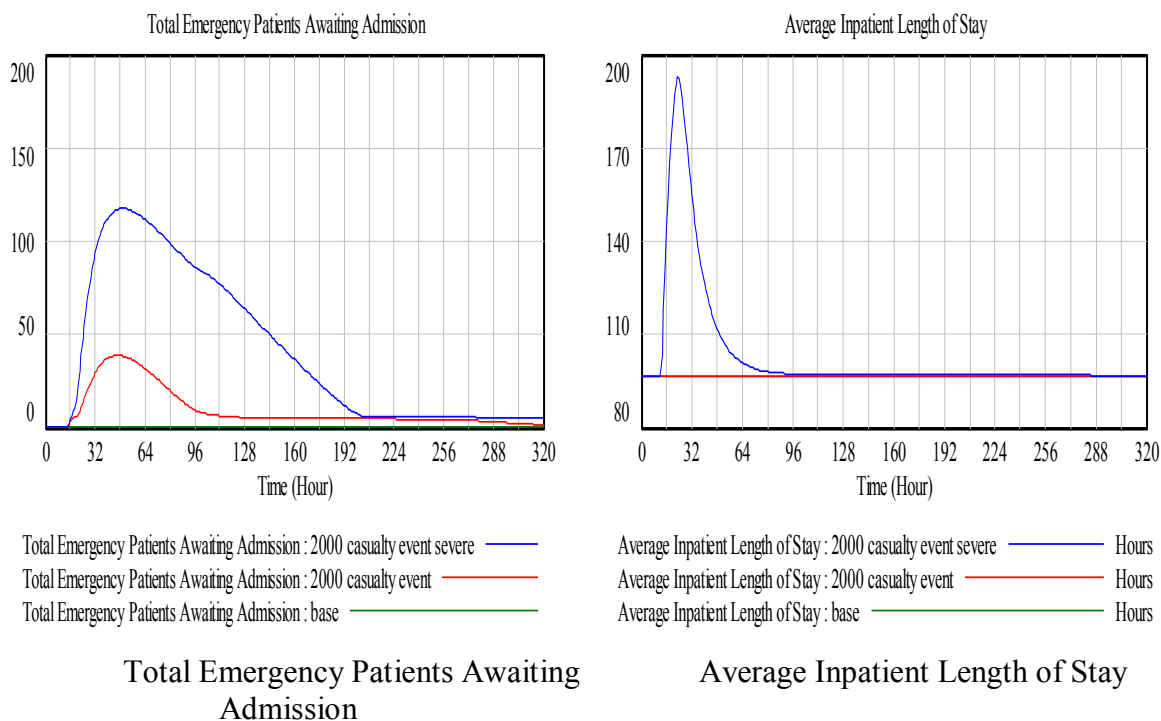
Figure 9: Effects of More Severe Injuries from 2,000 Casualty Event (Blue) vs. 2,000 Casualty Event with "Normal" Severity (Red)
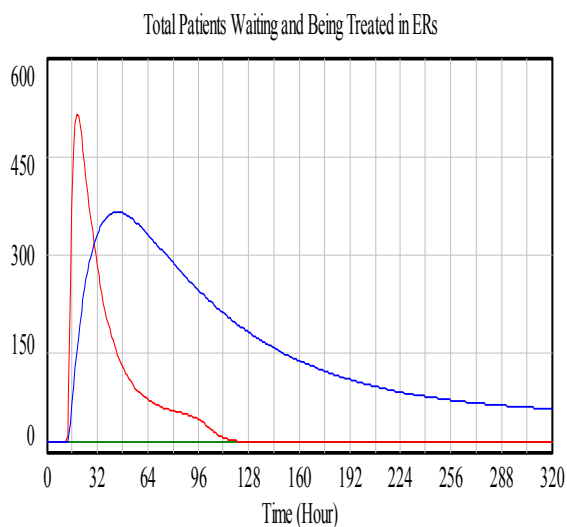
Contagion creates a totally different picture and a disastrous one if it is left unchecked. Figure 11 shows what happens when the original 2,000 people are exposed to a pathogen that causes them to get sick and then spread the disease to others. The results are displayed on graphs that also show what happens when a large-scale program of screening and prophylaxis is undertaken to stem the spread of the disease.

As shown in Figure 11, contagion results in the rapid spread of the disease and growth in the number of cases and cumulative deaths. The green line represents the simulation discussed above in which 2,000 people are exposed, but there is no contagion. The red line reflects the same initial exposure, but with spread by contagion to other people. The blue line shows the effect on the contagious disease of a timely program of screening and prophylaxis that is put in place after the first 100 cases have been detected.

Contagion produces very large numbers of additional deaths. After a while, the majority of the population has died or is sick and being treated or is temporarily disabled while recovering. There are very large numbers of people who require hospitalization, but cannot be admitted. In reality, these people would be on cots in a variety of public buildings or simply kept at home since they would so overwhelm the capacity of local hospitals. In fact, the problem is made worse, as shown in the fourth graph by the fact that so many of the health care personnel are disabled by the disease that some hospital beds normally available must be closed. In each of the graphs, the impacts of the screening and prophylaxis program are dramatic. In addition to reducing deaths, the program has a significant economic return as well.
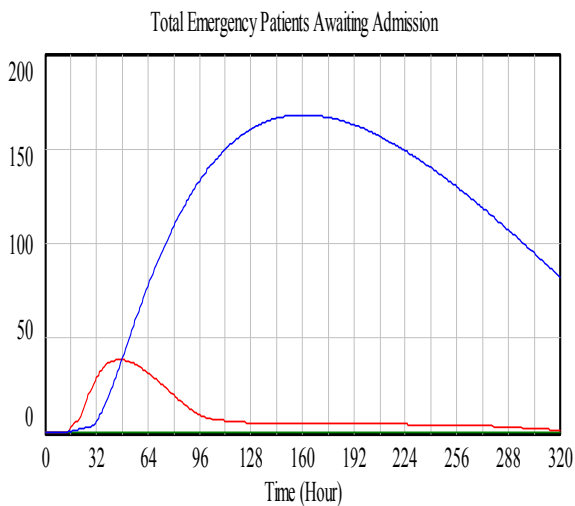
Total Cumulative Deaths

Total Patients Waiting and Being Treated
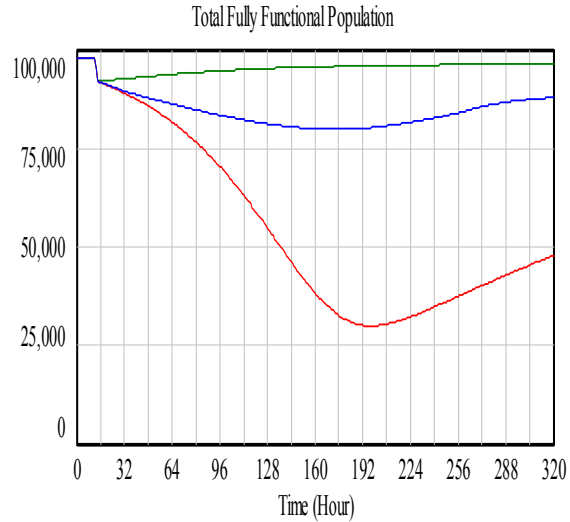

Total Emergency Patients Awaiting Admission

Total Temporarily Disabled

Figure 10: Effects of Dispersal of Pathogen with 2,000 Person Exposure (Blue) Compared to 2,000 Person Short Duration Event (e.g., Explosion) (Red)
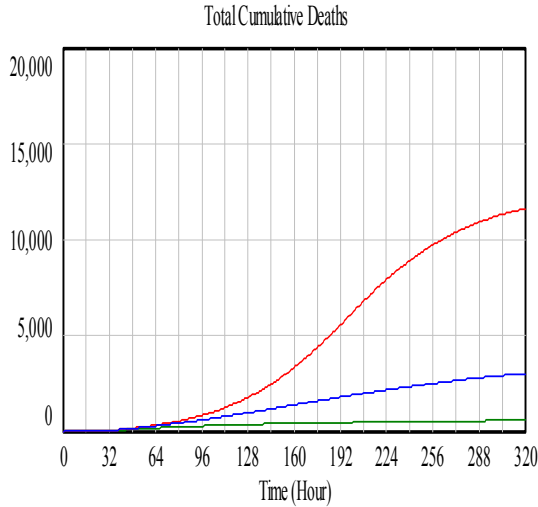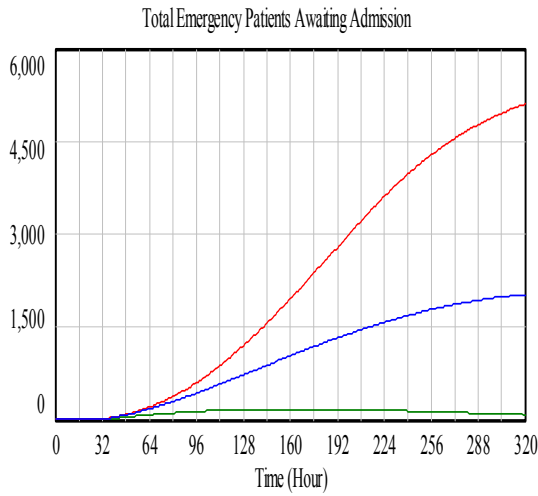
Total Cumulative Deaths

Total Fully Functional Population

Total Emergency Patients Awaiting Admission

Staffed (Hospital) Beds Available

Figure 11: Pathogen Exposure with Contagion Alone (Red) and with Effects of Screening and Prophylaxis Program Included (Blue) Compared to 2,000 Person Exposure without Contagion (Green)

Further Development and Use

These simulations are only a small sample of what can be done with the model. More extensive use of the model will provide a better understanding of the impact of these events on communities and the relative effectiveness of different prevention and mitigation strategies. Sensitivity analyses will help to identify critical parameters for which better data and/or structural elaboration are required. Use of case studies such as the bombing of the Oklahoma City Federal Building may also provide useful benchmarks for validating the model and improving its parameters. The model will also be elaborated and expanded in a number of areas to provide a more detailed look at the effects of different types of events and assure that it can be used to assess a wide variety of scenarios.

The model is designed to be scalable for different-sized communities with different levels of resources available. Applying the model using data from real-world communities will help to validate and calibrate it. It will also provide insights to decision-makers in those communities and, in turn, give a better sense of how this model and others can be made more useful for supporting emergency management and planning. The elaborated model will also help national and regional level decision-makers understand the role they can play in providing support to local areas that suffer major incidents and the potential impacts of simultaneous incidents.

Another possibility for further development would be putting an interface on the model that enables communities to put in their own data. This would then permit "hands on" use by decision-makers who can evaluate many different scenarios that might affect their communities and assess alternative strategies for dealing with each scenario. The advantage of having such a tool available in communities is that, over time, they can develop intuition about measures that help make the community less vulnerable to a wide range of hazards and are the most cost-effective and protective ones to undertake. Use of such a simulator would also provide a framework for conversations among different emergency agencies and health care providers and serve as an aid in planning multi-agency responses to major incidents. This approach proved quite useful for encouraging conversations among different agencies concerned with port security in the Pacific Northwest region of the US (Conrad et al, 2003).

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