Resiliency of Transportation Corridors Before, During, and After Catastrophic Natural Hazards

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A report submitted to the University of Delaware University Transportation Center (UD-UTC)

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Overview

The following dissertation "Managing Critical Civil Infrastructure Systems: Improving Resilience to Disasters" was submitted by Silvana Croope in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering. The dissertation was completed under the supervision of Professors Sue McNeil, Tracy Deliberty, Joanne Nigg, Nii Attoh-Okine and Daniel Leathers. The dissertation serves as a final report for the University Transportation Center project "Resiliency of Transportation Corridors Before, During, and After Catastrophic Natural Hazards."

In addition five working papers were developed that include detailed "how to" instructions for developing the data and models as follows:

Working with HAZUS-MH. Working Paper. University of Delaware, 2009

*Developing the STELLA model for a DSS for mitigation strategies for Transportation Infrastructure: Building the model in STELL*A. Working Paper. University of Delaware, 2010.

*Developing the STELLA model for a DSS for mitigation strategies for Transportation Infrastructure: Introduction to STELL*A. Working Paper. University of Delaware, 2010.

*Developing the STELLA model for a DSS for mitigation strategies for Transportation Infrastructure: Building the model's interface in STELL*A. Working Paper. University of Delaware, 2010.

*Developing the STELLA model for a DSS for mitigation strategies for Transportation Infrastructure: Testing the mode*l. Working Paper. University of Delaware, 2010.

The working papers are available on the University of Delaware University Transportation Center's website: http://www.ce.udel.edu/UTC/Publications.html

MANAGING CRITICAL CIVIL INFRASTRUCTURE SYSTEMS:
IMPROVING RESILIENCE TO DISASTERS

by

Silvana V Croope

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering

Spring 2010

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ABSTRACT

The Nation's capability for maintaining and improving infrastructure systems and assuring continued critical infrastructure systems' services has received special attention in the United States of America, largely due to recent disasters with significant impacts. A large number of research and policy studies have been conducted to develop methods to improve protection of critical infrastructure. One approach is to reduce the vulnerability of places and infrastructure systems through mitigation strategies that increase system resilience or resistance to the stresses imposed by disasters. Improving resiliency requires a system of systems approach because of its complexity. Critical infrastructure not only responds to the needs of society for the smooth daily continuation of activities, but also provides the basis on which society exists and relies. To address this complex problem a decision support system to develop critical infrastructure resilience strategies is needed. One such decision support system analyzes the problem using system dynamics. The Critical Infrastructure Resilience Decision Support System (CIR-DSS) developed in this research recognizes the impact of disasters including damage and disruption to critical infrastructure and loss of life. CIR-DSS development involves: a) understanding the operations and management of critical infrastructure, b) development of a framework to capture these processes, c) development of the model framework, d) development of the model, e) development of the model's interface, and f) the communication of the model results including risk and a cost benefit analysis of alternative strategies. A case study is used to test and validate the approach of the CIR-DSS framework. The CIR-DSS development takes advantage of existing software such as Geographic Information Systems (GIS), Hazards U.S. Multi-Hazard (HAZUS-MH), a tool to assess the impacts of natural hazards, and Structural Thinking, Experiential earning Laboratory with Animation (STELLA), a tool to build Systems Dynamics models. The case study used to test and validate the CIR-DSS approach is based on a real disaster that occurred in Sussex County, Delaware in 2006. The case study demonstrates: 1)

the wide range of data and resources required in supporting decision making, 2) how the concepts can be integrated into a decision support systems and 3) the insights gained in using system dynamics to structure this CIR-DSS complex problem.

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Infrastructure systems are critical for sustaining and maintaining a nation's socioeconomic system. Their importance is underscored by the need to maintain continuity of services. These critical infrastructure systems are also complex systems that are dynamic. The functionality of critical infrastructure systems is continually challenged by the aging process, disasters (both natural and technological), and constrained resources. In the past decade the concept of resilience, the ability of a system to withstand or respond to changes, has been used to explain the impact of disasters and other changes (Bruneau *et al*. 2003). These challenges and the desire to improve system resilience can be addressed by specific, improved knowledge, and decision support systems. The key question in this research is:

How is the resilience of critical infrastructure systems improved using information and decision support systems?

This research answers this question through an approach that consists of the development of a conceptual framework for a decision support system for infrastructure repair, replacement and serviceability in the aftermath of a disaster. Maintenance, repair, and rehabilitation actions aim to restore a system's performance and function immediately following the initial rescue operations related to of a disaster. The proper identification, processing and management of information are key elements in this process.

Recognizing that each type of critical infrastructure and each facility is unique, and that there is a large variety of types, extent, and impact of disasters, improving the resilience of critical infrastructure necessitates the application of the decision support system framework. By using the framework in a case study the benefits and constraints of such an approach are demonstrated, contributing to the state-of-the-art in this field. While the research is broadly applicable to all types of infrastructure, the focus is on transportation infrastructure and roads in particular.

1.2 Motivation

The Nation's capacity to maintain and improve infrastructure systems, and assure continuous service from critical infrastructure systems has received special attention in the United States due to recent large disasters impacts. Initiatives related to critical infrastructure protection include the reduction of vulnerability and governmental policies related to mitigation strategies to increase resistance capacity, and research to reduce vulnerabilities. The development of a decision support system to improve the resilience of critical infrastructure is consistent with these initiatives in recognizing the potential impact of disasters on infrastructure operation and management.

Specifically the proposed Critical Infrastructure Resilience Decision Support System (CIR-DSS) framework is intended to help mitigate problems, promote the need for better physical condition of systems to ensure functionality, and the continuity of operations by exploring the potential impact of disasters on infrastructure operation and management. This includes understanding;

- the nature of operations and management,
- the data and tools to support decision making and
- the consequences of failure, or degraded operations and performance.

Tools include the use of existing computational systems that provide a geographical context, analyze civil infrastructure systems, manage physical assets, and assess vulnerability and impacts.

1.3 Research Approach

To address the question posed *"How is the resilience of critical infrastructure systems improved using information and decision support systems?"* the research involved the following tasks:

- conducting a literature review,
- developing forms and metrics for capturing system resilience,
- developing a decision support framework for critical infrastructure, and
- applying the framework to a case study to demonstrate the application of the concepts and framework,
- the research requires the integration of concepts recognizing both a conventional and a new approach to infrastructure assessment to state-of-art methods.

Some of the key concepts are the infrastructure system itself, critical infrastructure system, disasters, resilience, vulnerability, mitigation, failure, and the decision support system. The main assessments identified are vulnerability assessment, damage assessment, and impact assessment. Some key concepts behind the development of the CIR-DSS are decision variables, framework, and models. These concepts are discussed and documented in a separate literature review and summarized in a glossary of Appendix A of this document (Croope and McNeil 2007). The remainder of this section explores the concept of resiliency in the context of the decision support system, explores the decisions that are needed, reviews the concept of decision making, and finally presents the framework. From a methodological perspective the research uses concepts from Systems Dynamics (de la Garza 1998) to capture the different stakeholder perspectives, the integration of a system of systems (Mendonça and Wallace 2006; Smith 1998; Croope and McNeil 2007), and the adaptation of the system to feedback. The system dynamics model is built using STELLA, a language to capture the flows that represent key variables in system dynamics models. GIS, spreadsheets, and HAZUS (FEMA's multihazard tool to model impacts) are used to process input data for the systems dynamics model.

1.3.1 Resiliency

Resilience of systems and communities and their activities relies on a shift from hardening sections of the infrastructure to a systems approach where hardening of the infrastructure is as important as the network system redundancy, robustness, rapidity, and resourcefulness. The concept and principles of resilience applied to civil engineering systems helps understand ways to deal with challenges such as failure and disruption of interconnected and interdependent critical infrastructure systems due to disasters and the need for service continuity. Resilience of systems is associated with activities that may include hardening of infrastructures, and considering the system as a whole. A resilient network should not fail because of some sections fail. A resilient network is the main goal for improving critical infrastructure systems. It means the "ability to provide and maintain an acceptable level of service when facing faults and challenges to normal operation" (Wikipedia contributors 2007d). This approach focuses on increasing the adaptive capacity of systems ensuring the inclusion of enough redundancy to provide continuity of function, by increasing the ability and speed of the system, and by evolving and adapting to new situations as they arise (Dalziell and McManus 2004). The identification and measurement of resilience is thus a necessary way to evaluate the results of system operations and improvements.

An analysis of system resiliency begins with a diagnosis or a before event assessment of a critical infrastructure (for example, the transportation system) in terms of system characteristics such as robustness, rapidity, redundancy, and resourcefulness (MCEER Earthquake Engineering to Extreme Events 2006). A network resilience concept is used, which means a system must continue to provide and maintain an acceptable level-of-service despite changes in or being submitted to stress different from its normal operations (Wikipedia contributors 2007d). Resilience characterizes the systems as having an inherent ability to restore itself to its former condition, or as having an adaptive ability/capacity (Bruneau *et al*. 2003). Figure 1 shows the approach given by Bruneau *et al*. (2003) to measuring resilience of an infrastructure system in the context of an earthquake. The measure Q(t), "the quality of the infrastructure of a community", varies with time. The infrastructure performance is the key measure for assessing resilience, and can range from 0% (no service is available) to 100% (there is no degradation in service).

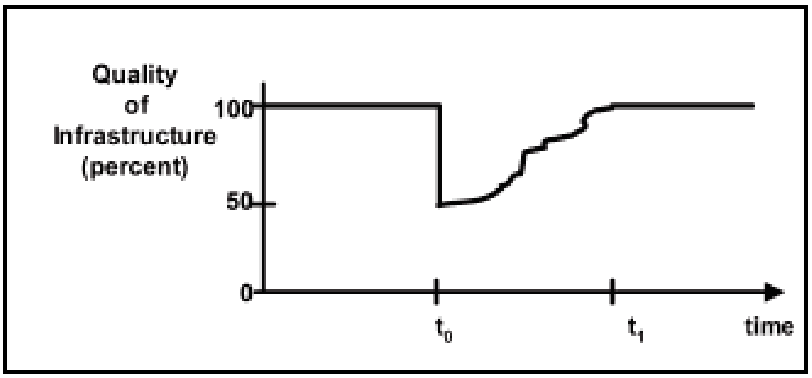


Figure 1 Conceptual Definition of Measure of Seismic Resilience
Source: Bruneau *et al.* (2003).

Resilience metrics for critical transportation systems can be used to help manage civil infrastructure problems and also for developing strategies of protection and ensuring continuous system operation. Some of the resilience metrics are performance (e.g. key performance indicators – KPIs) or safety measures, or also based on rating systems to capture system behavior. Resilience of systems is important because of decisions that take place at the individual, organizational and societal levels to cope with a partly unpredictable environment. These decisions can constitute a source of risk if entrenched in institutional or organizational norms, where trade-offs and sacrificing decisions become habitual. The life cycle of transportation assets can be designed, evaluated, forecast and maintained with the help of some civil infrastructure systems such as asset management, for example the Federal Highway Administration's Highway Economic Requirement System state version (HERS-ST) (USDOT and FHWA 2006), or the World Bank's HDM-4 (The University of Birmingham 2006).

The evaluation of the resilience of critical infrastructure systems and management is challenging due to the lack of tools that capture the operation of these complex, large, interdependent systems. This also makes it difficult to identify critical nodes, determine the consequences of outages, and optimize mitigation strategies. Resilience to unexpected events requires organizations and stakeholders to think beyond typical disaster scenarios.

1.3.2 Decisions, Decision Making and Decision Support

Considering that the focus of this research is on the resilience of critical infrastructure systems in a post-disaster arena, the model design must contain decision-making variables (Garuti and Sandoval 2005) that include the different participants and analysis evaluations to later assess consistency with government policies. Decisions related to disrupted critical infrastructure that focus on a post-event analysis can be divided into two areas: (1) a temporary fix and (2) a long-term plan of action to be included in the phases of disaster reconstruction and/or mitigation. To assess, forecast and communicate risk and failure, models and tools are used to build a decision support system, thus generating possible solutions, assessing consequences and impacts, and gaining insights into the interactions among the various stakeholders and decision-making units. The use of models and tools permits the analysis of problems and the development of solutions in a short period of time with fewer errors, and on a scale that goes beyond a single decision-maker (Kehlet 2007; USDOT and FHWA 2006; USDOT and FHWA 2007; Veldkamp and Verburg 2004).

Improving the resilience of critical infrastructure systems includes all these components: the infrastructure, disaster events, policies, decision-makers, resources, places, and analysis processes for developing solutions that will improve current conditions. The process of defining the problem, developing and choosing solutions is referred to as the decision-making process that is part of a decision support system.

Decision-making is a process that leads to the selection of a course of action born from different possibilities, producing a final choice that is either an action or an opinion (Wikipedia contributors 2007a). Decision-making considers the infrastructure system performance measures according to alternative projects, the frequency of events, the benefits and risk, and the project alternatives (including doing nothing). The adoption of a decision-making process, a method to analyze a problem, is to give structure to the problem to be solved through a hierarchical organization. The problem is divided into its fundamental components, which allows in-depth analysis of each specific issue and thus associate it with other measurements to produce the information needed to generate solutions (Garuti and Sandoval 2005). This research uses a structured rational decision-making process in a macro environment addressing complex critical infrastructure problems due to disasters through a decision support system framework. Analyzing risk and failure of critical infrastructures using a decision-making process enables the consideration of a large number of variables while keeping focus on the overall resilience of systems in seeking alternative solutions. The uncertainty existing in the occurrence of disasters is accounted for by specifying the likelihood of events and the post-impact options for building/increasing resilience of critical infrastructure systems.

A systematic decision support model is also useful to ensure decision consistency and capture interaction with a changing environment. Related decision tasks with a certain degree of logical relationships can help achieve a comprehensive solution for the entire decision-making problem (Liao 1998). Decision Support Systems (DSS) focus on specific decisions and supporting decision-making processes, not replacing the user's decision-making process. Geographic Information Systems (GIS) are complementary tools for Decision Support Systems in creating a Spatial Decision Support System (SDSS), for decisions that require spatial data (Keenan 2004), for example transportation.

The data required for a DSS for critical infrastructure resilience needs to be good quality from defined datasets with a specific level of detail (scale), in a useful format, and have defined standards for collection, access, and storage. In addition to data for the critical infrastructure and potential disasters (the main components), a set of subcomponent datasets are required. The main components must have common intersection data (to support indexing and referencing of all related data) to enable analysis for the systems dynamics diagram for Critical Infrastructure Resilience Decision Support System (CIR-DSS).

1.3.3 CIR-DSS Framework

Considering all the concepts, assessments, and basis for a DSS, the development of the CIR-DSS framework evolved into the following these steps:

Step 1: Rethinking what, why and how decisions are made, thus adjusting processes and/or building new analysis processes to quantify the system's resilience.

Step 2: Setting up boundaries and variables used for building the framework. This can be accomplished by choosing one type of hazard and one type of critical infrastructure to develop the CIR-DSS framework, demonstrating how such an approach can be used for improving the resilience of systems while managing different project options to find the best trade-off possible under certain conditions.

Step 3: Thinking about the process for such an analysis and the type of outcome that may be reached, choosing among options to obtain the expected objective in different ways or on different levels in terms of precision and accuracy.

Step 4: Evaluation of expected results as compared to results obtained from the framework.

Step 5: Validation of the developed framework through its application in a case study. The case study must consist of a direct application of the developed framework, analysis and final remarks or conclusions.

The decision support system framework considers the individual systems including the intended purpose, way of operating, safety parameters, visibility in terms of security issues, and the criticality of each different type of critical infrastructure and its components. The framework also requires the recognition of the interdependencies among different infrastructure types, by understanding the role of the critical infrastructure being analyzed in relation to the other types of infrastructure. The goal is to improve resilience, performance measures and safety measures of the system. The framework is structured to evaluate the effectiveness of the system in addressing these goals. The proposed framework is referred to as a Critical Infrastructure Resilience Decision Support System (CIR-DSS) framework.

1.3.4 Model Development

Using this framework the model is developed following these steps:

- a literature review, and identification of current gaps and needs for resilience of critical infrastructure systems on a system of systems approach including documentation of the state-of-the-art in defining and applying concepts of resilience;
- development of a conceptual model and a system dynamics diagram for addressing resilience of critical transportation infrastructure systems challenged by flooding as a type of disaster;
- application of the model using both real world and laboratory data to fill in data gaps and needs to approximate real world solutions; and
- analysis of the results and assessments of the needs for complementary and/or future research.

The CIR-DSS framework must:

- Account for constraints such as resource limitations (monetary, temporal, equipment or materials).
- Take advantage of both human and computational sources of support (Holsapple Unknown).
- Recognize that the process of making choice requires the support of tools and techniques for estimation, evaluation and/or comparison of alternatives.
- Appreciate that a single DSS usually does not fit neatly into one category of application, requiring a mix of two or more architectures.
- Represent the system attributes, such as geographic location and network connectivity of each type of critical infrastructure system.

- Assess performance measures such as resiliency and vulnerability both before and after a disaster.
- Draw on experiences in asset management in evaluating actions that address various goals objectives and policies.

1.4 Research Objectives

The main objective of this research is to develop the Critical Infrastructure Resilience Decision Support System (CIR-DSS) framework to improve the resilience of critical infrastructure systems that are likely to be impacted by disasters. The framework for the CIR-DSS consists of interconnected analyses that provide information for decision-making considering:

- the sequence of events and disruption caused by a disaster (response, recovery, mitigation);
- the range of possible decisions relating to mitigation recognizing the economic trade-offs that are captured using asset management principles, and performance measures that evaluate system resilience; and
- insights into the opportunities for improving the resilience of the infrastructure system.

The research also requires establishing:

- common and consistent terminology,
- an appropriate level of analysis, and
- performance metrics that capture the resilience of systems considering the various institutional hierarchies in infrastructure decision making.

The emphasis is on post-disaster impacts that define the time frame for the problem analysis. Recognizing that disasters occur at specific points in time and space, we are interested in actions taken prior to the disaster to improve the resilience of the system such that after the disaster the damaged or disrupted critical infrastructure can function or be restored to normal function as soon as possible after the event. That is, we focus on the recovery and mitigation phases of disaster for critical infrastructure. This focus is not simply on the temporary fix that usually takes place immediately after the disaster; but on the medium and/or long-term actions that involve restoration and "hardening" of the infrastructure.

This post-event time frame gives the opportunity to:

- assess risk and failure, and
- include resilience concepts and principles in
  - the maintenance, repair, rehabilitation and/or reconstruction of infrastructure, and
  - new construction projects related to critical infrastructure by improving performance, strength, and enhancing the infrastructure's ability to withstand and adapt to different levels of stress.

The assessment can be used to choose projects that are either standard projects or projects that enhance the resilience of the infrastructure to disasters. The improved process as applied to reconstruction and new construction must be integrated into planning and disaster protection, which usually starts after the damage assessment (in normal project process time), and may take several years to complete. This need for incorporating long-term post-disaster rehabilitation and reconstruction programs, as well as short-term emergency relief and recovery programs, in comprehensive regional development planning processes was addressed in the United Nations' General Assembly, resulting in a resolution designating the 1990s as the 'International Decade for Natural Disaster Reduction- IDNDR' (UNCRD and World Bank 1990). The objective is to reduce the loss of life, property damage, social, and economic disruption caused by natural disasters, through concerted international efforts.

The spatial, economic, social, political/organizational and technological dimensions of a critical infrastructure system influence the analysis of risk and failure assessment, forecasts and communication. The result of these activities can be used to improve security, safety, reduce loss of life, and reflect the more efficient use of money/financial resources.

1.5 Dissertation Outline

This dissertation documents the model development process outlined above. The dissertation is organized as follows:

- This introductory chapter (Chapter 1) presents the problem statement and motivation for the research, introduces key concepts and the research approach, defines the objectives and scope of the research, and outlines the steps involved in model development.
- Chapter 2 provides background and a review of relevant literature. This includes decision support systems, system dynamics, tools to develop system dynamics models, the basics of working with STELLA, the benefits of using STELLA, tools to assess impacts and an overview of HAZUS-MH, and finally examples of decision support systems related to disaster decision making.
- Chapter 3 presents the framework for the Critical Infrastructure Resilience Decision Support System including an overview of the framework, the process for developing the framework into a decision support system and the implementation of the framework.
- Chapter 4 presents the case study material that is used to develop the models including sources of data and model inputs derived from other software.
- Chapter 5 details each of the eight steps involved in developing the model in STELLA and reviews testing of the model.
- Chapter 6 describes the strategy for developing the interface and an example of the annotation for Step 6 of the model building to illustrate how the model development process can be portrayed.

- Chapter 7 presents the model results and an evaluation of the results.
- Chapter 8 is the conclusion and directions for future work.
- Chapter 9 describes the contributions.
- Appendix A defines the terminology.

The dissertation is supported by five working papers that include detailed “how to” instructions for developing the data and models as follows:

- Working with HAZUS-MH, (Croope 2009) Section 4.6.
- Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Introduction to STELLA, (Croope 2010b) Section 3.4.
- Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Building the Model in STELLA, (Croope 2010a) Chapter 5
- Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Testing the Model, (Croope 2010d) Section 5.12.
- Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Building the Model’s Interface in STELLA, (Croope 2010c) Chapter 6.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

The framework and model developed in this research are grounded in system dynamics and decision support systems using concepts of resiliency. This chapter briefly reviews the concepts and tools used to develop the decision support system. Appendix A is a glossary of the terms and terminology used in this dissertation.

2.1 Decision Support Systems

Systematic decision support systems are intended to ensure consistent decisions and recognize the need to relate the decisions to the changing environment. Structuring tasks based on logical relationships helps to develop a comprehensive solution for the entire decision-making problem (Liao 1998). Decision Support Systems (DSS) focus on specific decisions and on supporting decision-making processes, but cannot replace the user’s decision-making process. We refer to the proposed DSS as a Critical Infrastructure Resilience Decision Support System (CIR-DSS). This subsection provides examples of relevant subsystems and identifies appropriate decision variables.

2.1.1 Subsystems

A decision support system can also include a number of subsystems that support the process. For example, Geographic Information Systems (GIS) can be a part of a DSS and capture the relationships among spatial data (Keenan 2004); a specific example is the transportation network.

Another example of a possible subsystem is the tool Hazards U.S. Multi-Hazard (HAZUS-MH), developed by the Federal Emergency Management Agency (FEMA). HAZUS-MH is a “nationally applicable standardized methodology and software program that estimates potential losses from earthquakes, floods, and hurricane winds” (FEMA 2007c). Loss estimation provides a basis for mitigation plans and policy development, as well as emergency preparedness, and response and recovery planning at all levels of government and in their decision-making process. A final example is the use of the Highway Economic Requirements Systems – State Version (HERS-ST) to support decision making related to roadway improvements (USDOT and FHWA 2006).

2.1.2 <u>Decision Variables</u>

The decision variables in a decision support system need to capture different factors, scales and stakeholders in play (Garuti and Sandoval 2005). These differences are explored in this section.

As explained by Crain (Crain 2007), "a prime goal of any state-of-the-art general management simulation model is to develop and test strategic policy initiatives for the organization". Considering that the focus of this research is on critical infrastructure resilience of systems in a post-disaster context, the model design must use decision-making variables that capture the perspectives of different participants and can be used to analyze and evaluate the relationships among government policies, investment options and consequences.

Before, during, and after a disaster event, the infrastructure metrics will vary. In the long term these metrics will also change as the decision variables change value. The post-event scenario includes disrupted critical infrastructure and looks at the damage of critical infrastructure. The decision variables view the alternatives for fixing the damaged parts of the critical infrastructure. This can be generally divided into two approaches: (1) a temporary fix and (2) a long-term plan of action to be included in the phases of disaster reconstruction and/or mitigation. This research focuses on the critical infrastructure system resilience used in the post-disaster event long-term plan of action included in the reconstruction or mitigation phases of the disaster event. Decision variables that can be captured in the analysis include the choice of projects, level of investment, condition, and timing of investment. Although the activities associated with the reconstruction and mitigation phases of a disaster can be distinguished, there is no clear differentiation in time between when one phase ends and another begins. Both phases are therefore considered when identifying a solution to or improvements in critical infrastructure system resilience focusing on the post-disaster period.

Because the resilience of a critical infrastructure system is a complex analysis problem, the decision-making variables must capture the multiple perspectives involved in the strategic analysis, helping to avoid bad or disastrous results from pre-determined plans. The technological perspective must be understood as part of an overall analysis including organizational and personal perspectives, when these decisions impact large numbers of people (Linstone 2000).

This means decision variables must be identified in such a way as to enable a flexible approach and provide the decision support system the ability to recognize and capture:

- different stakeholders' perspectives of projects and consequences,
- technological or process innovations, and
- changes in policies or new policies that impact the problem.

Decision variables are those elements needed to properly capture the changes in the model being developed and the overall objective of the model. The decision variables for improving the resilience of critical infrastructure systems consist of variables that capture the spatial, economic, social, political/organizational and technological dimensions that are included in the CIR-DSS framework and model. The decision variables are the actions. The most relevant parameters are summarized and identified in defining the scenarios being considered. For example, the risk of failure uses a parameter to describe the likelihood of a certain type of disaster at a certain location. The vulnerability assessment of the critical infrastructure considers the type, condition and performance of infrastructure, geographic features and assumed post-disaster damage for a specific period of time focusing on the reconstruction and mitigation post-disaster phases.

The decision support system for critical infrastructure system resilience uses a large number of variables - inputs, outputs, and states. The state variables describe the behavior of a dynamic system (Wikipedia contributors 2009), which in this case can be identified as the "resilience" variables. However, when resilience variables are looked at together with variables such as recovery and mitigation project costs and its benefits, these state variables take on different values depending on the decision variables that represent the alternative infrastructure fixes and improvements. Input and output variables, in a model with a lot of input variables, can be identified as the necessary variables to do a sensitivity analysis by changing their parameters to determine the changes in the system, addressing the robustness of the model (Wikipedia contributors 2010). The chosen input variable for the sensitivity analysis was a "damage" value of impacted infrastructure, and output values were the "net present value" of recovery and mitigation projects for different frequency event probabilities.

2.2 System Dynamics

A Systems Dynamics (SD) approach is proposed for the CIR- DSS framework. System dynamics is used to represent the sequence of events, the relationship among decision makers (e.g. DelDOT, FHWA, FEMA, and stakeholders) that play major roles, the types of policies that enabled certain actions (e.g. FEMA's Mitigation Grant), and the critical infrastructure system (e.g. transportation – roads) throughout different conditions and performances resulting from the stress imposed on the infrastructure by the hazard. System dynamics is a way to recognize that the critical infrastructure system and the disaster together are a complex problem (Dhawan 2005; Wikipedia contributors 2008).

This approach captures the behavior of the system including the perspectives of different stakeholders, inherently strengthening the system in a flexible and adaptable way based on feedback, allows the system to be reduced to subsystems that require specific types of information for each component, and supports information flow and feedback mechanisms.

The feedback mechanism used is based on the SD methodology that consists of a systematic process that views complex feedback structures (a control mechanism) to verify data and analysis results allowing for adjustments to and inclusion of more data, and the adjustment of parameters in a computerized simulation model (Dhawan 2005; Dictionary.com 2007). This feedback mechanism helps to develop a more robust hypothesis generation, hypothesis verification, and final adjustment for mitigation strategies (Mirmehdi, Palmer, Kittler, and Dabis 1996). The complex feedback includes parameter optimization through the processing chain, and high level inputs of decision-makers for the resulting improved critical infrastructure system resilience through mitigation strategies.

The feedback from mitigation strategy hypothesis generation provides the first insight developed. The vulnerability analysis confirms or rejects a strategy on the basis of the impact and damage assessment. The feedback for mitigation strategy hypothesis verification, which includes the asset management and financial systems considerations, is used to accept, reject, or include solution alternatives from the hypothesis generation. This includes looking at the different mitigation project approaches chosen, damage value per segment, causal agent, calculation, and assumptions made for the overall mitigation project of the infrastructure network.

The SD diagram used to represent the CIR-DSS framework shown in Figure 2, modified from de la Garza *et al.*, (1998), is based on mental models, which were then used to develop the computer-based software tool in STELLA, and later simulated using the most likely values of variables (Dhawan 2005). The framework is modeled to test whether the recognized framework for improving critical infrastructure system resiliency changes with the hypothesized system dynamics and developed mitigation strategies. This process helps viewing the interconnected system rather than just viewing isolated parts.

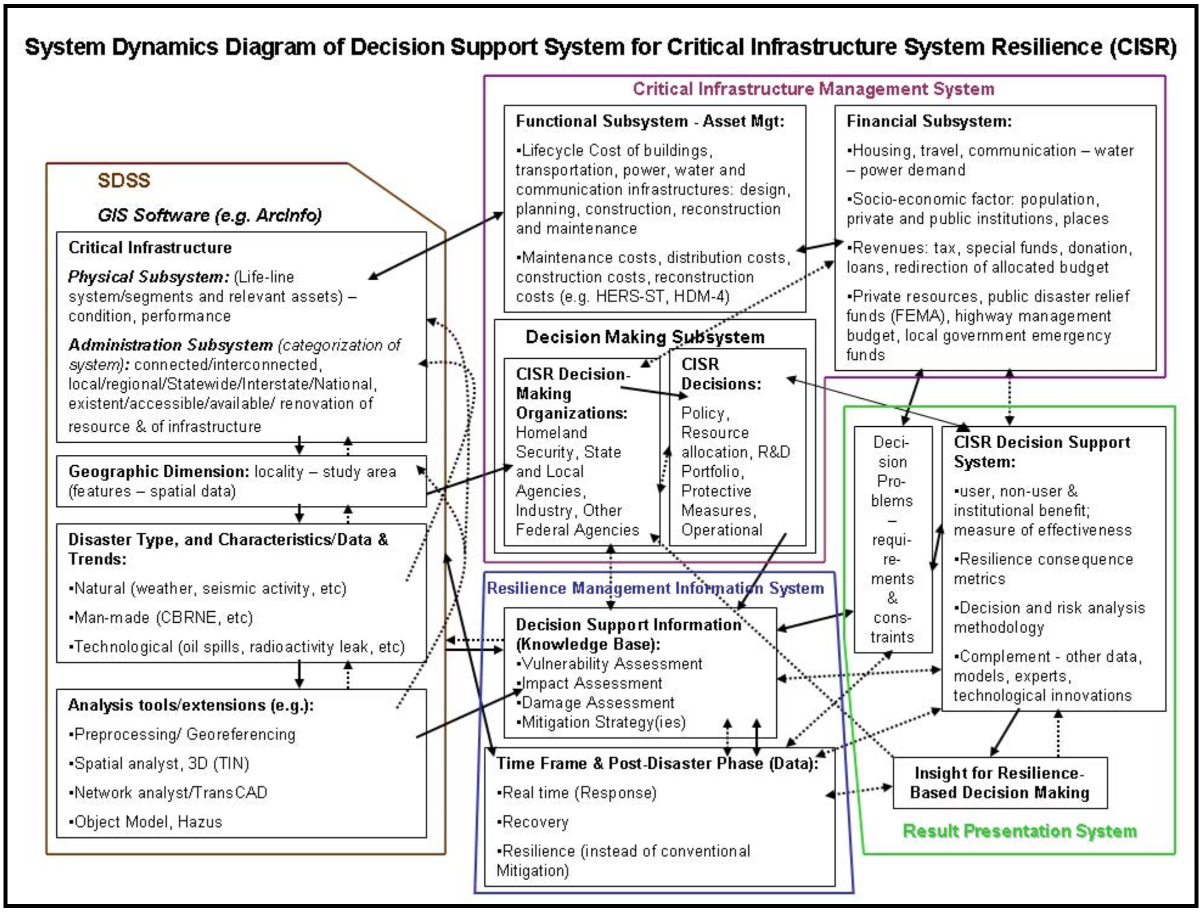


Figure 2 Systems Dynamics Diagram for Critical Infrastructure Resilience Decision Support System

Source: Modified from de la Garza *et al*. (1998).

The model development in STELLA uses SD techniques to see how the structure of the system governs its behavior through the analysis of feedback loops and computer simulations (Dhawan 2005). It helps improve the mental models of decision makers by looking at how policy determines behavior. The model views the financial implications of decisions by including variables that represent

- FEMA mitigation grants,
- project financial shares among stakeholders,
- final level of protection by infrastructure mitigation projects,

- infrastructure mitigation projects future impacts and benefits considering future other disasters, and
- these benefits calculations.

The improvement in system resilience viewed using system dynamics is the metric for the critical infrastructure system. This metric shows both the strength (value of resilience of the infrastructure system before and post-disaster system improvement), and the capacity for flexibility and adaptability after a disaster (Tierney and Bruneau 2007).

2.3 Tools to Develop System Dynamics Models

To build a computerized model consistent with the CIR-DSS framework, the options are to either build a tailored model or use an existing system. The tailored approach could take a long time to develop, be expensive, and need computer programming skills, which is not the objective of this research. Using existing software that fits the purpose of this research, is more reasonable and feasible, builds on available and accessible systems, and is consistent with the available resources and current skills. After considering some software systems (e.g. Excel, Microsoft Access, others), the STELLA software was chosen, despite not being ideal for including the original outputs from some of the systems used by CIR-DSS (e.g., HAZUS-MH), such as analysis of digital maps.

STELLA is the union of skills, specific language, representations, and programming that enables building models associated with thinking, communicating, and learning processes. In this sense, STELLA can be identified as a specific language used to represent relationships between elements of the system, capturing the behavior pattern associated with this relationship, increasing accuracy of descriptions and efficiency, and effectiveness of communication. STELLA can also be identified as a process for encouraging systems thinking skills, which includes system dynamics. The STELLA mapping process facilitates mental simulation, which is readily convertible into a computer model to enable simulation. STELLA can also be identified as software that works in the same way as writing a good composition, enabling evolving thought processes, communicating, and learning capabilities.

First, it is important to highlight that the diagram representing the CIR-DSS is the model for understanding the connection between:

- the external parameters and the system, the system's quantities (referred to as stocks in system dynamics) which accumulate values and reports the status of a condition,
- the flows-connection-relationship between the stocks, and
- the possible decisions or thresholds that can cause a system to develop new behaviors or branch into new states (Starting Point 2006).

Simple software is unable to show these elements, which include the feedback among the system variables, and different levels of interaction between the subsystems and elements. When considering the environment and end users of the framework for critical infrastructure system resilience improvement, it is important to have organizational learning. Organizational learning, according to STELLA (isee systems 2004), refers to "learning that is captured, and then somehow stored, outside the bodies of the individuals who create and make use of it".

STELLA software is focused on research that uses/draws maps to facilitate mental simulation, readily convertible into models that can be simulated by a computer (isee systems 2004; isee systems 2008). Internalizing the systems thinking skills, as well as the language and methods used by STELLA is a conceptual challenge that goes beyond the mechanics of learning the software. Because of these challenges, the guide for working with STELLA software (isee systems 2004) is divided into two sets of skills: systems thinking language (operational, closed-loop and non-linear), and the writing process (10,000 meter, system as a cause, dynamic, scientific and empathic thinking). Systems thinking language skills are described as:

- Operational - a way to link sentences from a stock in one sentence to a flow in the other, or from flow to flow. It's a way to represent the relationships between the elements making some assumptions about their general nature, via a structure of serial cause-and-effect relationships (laundry list), or perspectives such as synchronicity and God’s hand.

- Closed-loop - a shift from the laundry list view (causality runs one-way, static in nature), to system thinking view (two-way, or closed-loop, an ongoing process or dynamic). A reality view made of a web of closed loops (or feedback loops) is able to structure relationships between elements in mental models. It enables better anticipation of unintended consequences and short-run/long-run tradeoffs (more effectiveness) that help identify main intervention points.
- Non-linear - a way to capture behavior patterns that frequently arise in both natural and social systems. It enables better anticipation of the impacts of actions, as well as the initiatives that will be implemented to address the pressing social and environmental concerns to be faced in the future. The causal factor impacts the effect by a variant not always proportional magnitude.

The writing process skills can be described as:

- 10,000 meter - horizontal expanse vision with little vertical detail (big picture without fine discriminations).
- System as a cause - count vertical bias toward the inclusion of too much detail in the mental model representations. Mental models should contain only the elements where the interaction is capable of self-generating the phenomenon of interest.
- Dynamic - helps to filter out the non-essential elements of reality when constructing a mental model. Provides distancing from the details, and is applied to the behavioral, not the structural dimension. It also encourages a push back from the events and points to see the pattern of which they are a

part, making the mental model capable of dealing with a dynamic, not static, view of reality.

- Scientific - helps to be careful (investigative approach) and test models. It investigates possibilities and results obtained from models.
- Empathic thinking - helps broaden and improve communication, transmission of experiences, and knowledge by considering the other person's perspective.

Details for working with STELLA are presented in the next Section.

2.4 Basic Knowledge for Working with STELLA

The STELLA software is a product from i-see™ Systems Inc. This section shows some of the basic elements and their representations according to the guide for STELLA software. This section also presents an initial approach for using STELLA in the CIR-DSS framework.

STELLA uses a series of symbols to represent the dynamic behavior of the system. The STELLA software guide starts with the explanation of stocks (nouns, e.g., population, water, quality, commitment). These can be reservoirs, conveyors, queues and ovens (shown in Figure 3). They exist at a point in time, and are designated or written with capital letters. Stocks tell you how things are in a system.

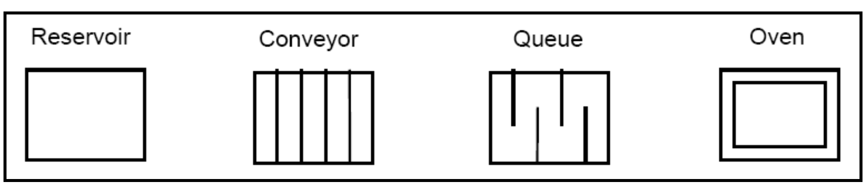


Figure 3 Stocks Types in STELLA
Source: Modified from isee systems (2004).

Each stock has a different function (characterized by a noun), which is shown as a summary in Table 1.

Table 1 Stocks Function and Examples

Stocks	Function(s)	Example(s)
Reservoir	Total number of entities - houses the net of what has flowed in, minus what has flowed out.	Water, population, cash.
Conveyor	The quantity that arrives at the slat - the one arriving at the "first slat" gets on and occupies it alone (not sharing the space), and rides (transit time) until the conveyor deposits it at the other end.	Like escalators - pipeline delays, aging chains.
Queue	For discrete event simulations. A line that is developed when things arrive at a rate that exceeds the capacity to process them. Retains both arrival integrity and batch size.	Cars stacking up at the tollbooths or cars amassing at a rotary (round-a-bout).
Oven	For discrete event simulations. Entity arrives, if the oven is currently baking (busy, or in operation), the entity waits (in a queue or a reservoir) and when (process) completely done, it exits. The entity that's waiting enters up to the capacity of the oven (limits/ thresholds determined), or until the doors open time expires. Entity then bakes/operates for the length of the oven's bake time, and it's then discharged.	Like elevators, depends on door open or closed to ride, and can have a queue waiting to ride it.

Source: Adjusted from isee systems (2004).

Another basic element is flow. Flows are designated with verbs. Verbs exist over time, are not written with capital letters, and indicate how things are going. Occurring flows update the magnitude of stocks. When there are no flows, system conditions remain static. Flows are responsible for the dynamics of the system, and can be physical (e.g., eroding, delivering, dying, in-migrating, and raining) or non-physical (e.g., building self-confidence, discussing, and learning) in nature.

There are two flow varieties, and one wrinkle shown in Figure 4.

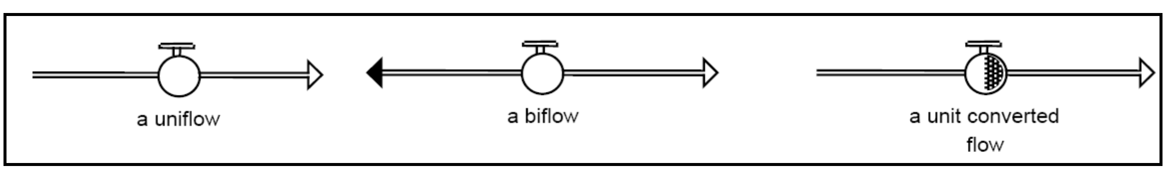


Figure 4 Flow Types in STELLA
Source: modified from isee systems (2004).

The flow characteristics per type are presented in Table 2.

Table 2 Flow Types in STELLA

Flow Type	Characteristics
Uniflow	- standard type, unidirectional indicated by the arrowhead; - uniflow pointing *into* a stock - *fills* the stock (and vice versa); - if inflow calculated value is negative (flow drains the stock), value is over-ridden by a value of zero - inflows cannot operate as outflows.
Biflow	- bi-directional flow, flow volume goes in *both* directions, either into or out of a stock; - general use rule: processes governing inflow/outflow to a stock are identical in nature; - example: velocity.
Unit Converted Flow	- used to make sense to convert the units-of measure of what's flowing, while it's flowing; - example: pull two Hydrogen and one Oxygen atom out of respective stockpiles and make one, rather than *three*, water molecules.

Source: Based on isee systems (2004).

By putting nouns and verbs together in sentences STELLA captures the behavior of the system. There are two types of sentences – simple and compound. Simple sentences involve one stock, with associated flow(s). Compound sentences (or infrastructures, spinal cords, or main chains) involve two or more stocks linked by at least one flow. The sentences must respect unit consistency, and conservation laws (law of conservation of matter and energy), unless dealing with non-physical variables (with the exception of the quantity of time). The addition or subtraction of quantities of non-physical variables does not interfere with the condition of others (e.g. knowledge, anger, commitment) since they do not operate in a zero-sum manner.

The real challenge emerges when sentences are linked. Initially the process follows operational thinking. As issues being modeled get more complex, other types of thinking skills are needed for building models. These types are closed-loop and non-linear. There are two possible operational thinking ways to link sentences; stock to flow, or flow to flow. To link stock to flow or flow to flow, a wire called a connector is used. There are two types of connectors:

1) A solid wire – the action connector that transmits an action or ends a process;
2) A dashed wire – the information connector that serves as an input, begins a process, or is used to arrive at a decision.

There is a decision logic that is not usually visible in the model representations, a space-compressed Decision-Process Diamond (DPD) usually shown as a diamond geometric figure. The idea is that information leads to a decision, and a decision leads to an action. This feature of STELLA is not used in implementing the CIR-DSS framework.

The action wires in a model convert the resulting decision into an action that is manifested as a change in the volume of flow. Only information connectors attach to DPD’s, but both types of wire can come out/be transmitters from a DPD - action will be taken as a result of the decision and information about it or the inputs to that decision. No connectors can be used to represent a conserved-flow linkage. Stocks do not flow through the wires. Flows transport and wires transmit. Connectors are inputs and outputs, not inflows and outflows.

Another element in the STELLA language is the converter, which is used to represent productivity. The converter plays the role of an “adverb”, modifying the verb (or flows). The converter tells about the how much per unit of the driver is contributing to an activity being made, a flow, or a stock of that activity. It is expressed in relevant units (e.g., knowledge/time). An example of the algebra is shown in Equation 1.

Equation 1 Converter Example for Working with STELLA

$$\underset{(knowledge/time)}{\text{your learning}} = \underset{(pages/time)}{\text{your reading}} \times \underset{(knowledge/page)}{\text{your learning productivity}}$$

Source: isee systems (2004).

Other possible uses for converters are: performing algebraic operations (summing or division), representing exogenous inputs, and substituting either stocks or flows that are still being chosen to be represented in the model. Converters can also change over time. Figure 5 shows examples of the use of a converter.

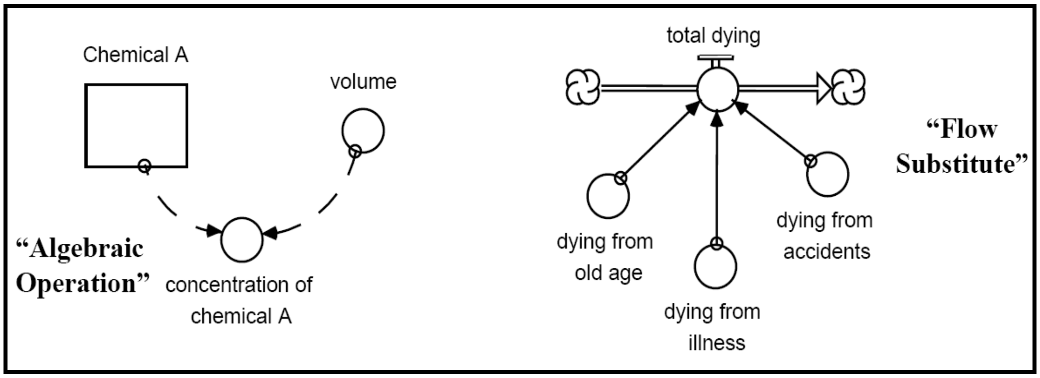


Figure 5 Converter Uses
Source: Modified from isee systems (2004).

Before putting these elements together to write sentences, two rules must be observed. The first is to respect unit consistency (units-of-measures) between stocks and the attached flow(s) - they must be the same, except when using unit conversion. The second is to respect conservation laws (same as matter and energy in physics). The exception to this law in modeling is by making a conscious decision to end a particular chain, not modeling nonessential elements, and when using a stock to represent a non-physical quantity other than the quantity of time. Non-physical variables do not obey this law, and do not operate in a zero-sum manner (e.g., anger, knowledge). The addition or subtraction of non-physical quantities does not interfere with the condition of other variables.

STELLA models using the stocks, flows, connectors, and other elements such as DPD's, are organized in templates that can represent flow formulations such as the *stock-generated* formulation (called External Resource Template), or the *flow-generated* formulation (called Co-flow Template), as shown in Figure 6.

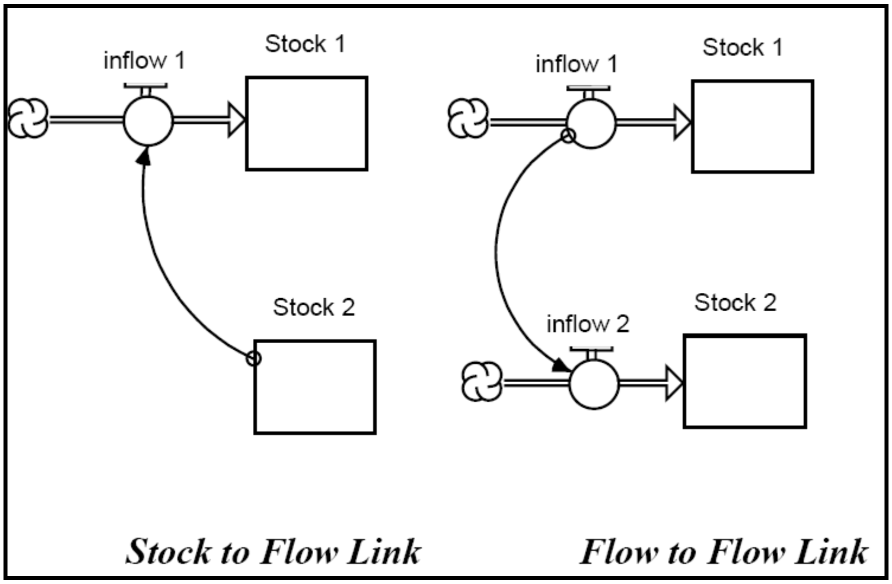


Figure 6 Possible Ways to Link Sentences
Source: Modified from isee systems (2004).

Some of STELLA's common templates that can be used to guide building models are briefly listed and characterized bellow.

- External Resource Template – used when some resource, other than the stock to which the flow is attached, provides the basis for producing the flow. Rather than the stock generating its own inflow or outflow, the flow is generated by a second stock (an external resource), which has an associated productivity.
- Co-flow Template (coincident flow) – useful to represent an activity that is driven by another activity, or to track an attribute associated with a stock. The co-flow is typically defined as the product of two flows.
- Draining Template – used to represent a passive decay process, where the flow is generated by the stock out of which it is flowing. The flow (an outflow from the stock) is the product of the stock and a loss fraction, or the stock divided by a time constant (the reciprocal of the decay fraction). This indicates that the average length of time resides in the stock, in a steady-state.

- Stock-adjustment Template – used to represent situations where a stock adjusts to a target value, and the way that perceptions, opinions, and the like, are adjusted. The flow is bi-directional! Whenever a discrepancy exists between the stock and the target, the flow will adjust the stock toward the target. The target and the adjustment fraction/time constant are usually converters but can be stocks.
- Compounding Template – used to represent a self-reinforcing growth process - flow generated by the stock into which it is flowing. The inputs to the flow are the product of inputs. A compounding fraction (a stock or a converter) has its unit-of-measure as units/unit/time. The units are denominated in the stock. A compounding fraction is equal to how many new units are produced by each existing unit within the stock, per unit of time.

Examples of template diagrams are shown in Figure 7.

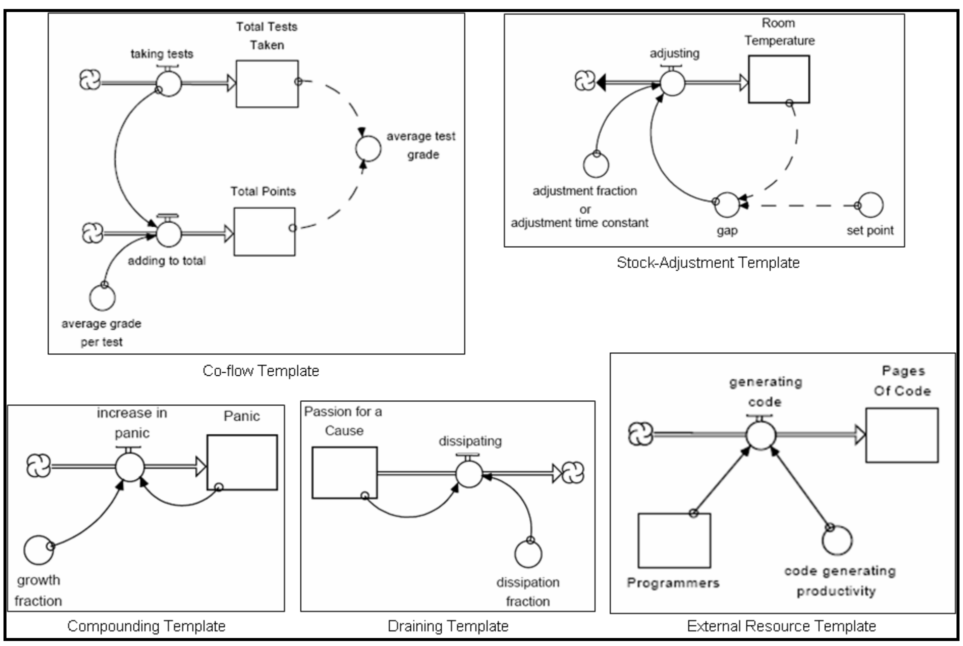


Figure 7 Templates Diagram Examples in STELLA
Source: Modified from isee systems (2004).

The cloud refers to a starting or ending point related to the subject being addressed.

To construct more complex sentences in STELLA such as closed loop and non-linear thinking, feedback loop parameters are allowed to vary, and feedback loops are extended to involve more than one sentence. This enables feedback loops a richer variety of dynamic behavior. This is represented as a graphical function in STELLA software that can be added to the diagram and represented by a sign of loss of innocence (~) – a relationship between an input variable and an output variable. The graphical function:

- indicates how an output variable will change as the associated input variable changes (a consequence of movements in some other variable – e.g. the impact of saturation);
- expresses the bi-variate relationship by making use of a sketchpad with a grid on it by resorting to mathematics;
- draws the relationship envisioned (view a hypothesize relationship between only two variables where interaction is against all other things held constant);
- enables non-mathematically-inclined people to express relationships largely limited to a mathematician's domain;
- is used to represent structural relationships within the model, meaning they are not graphs of model output over time;
- enables feedback loops to change in strength (shifts in feedback loop dominance) over the course of a simulation.

The slope of curve of the graphical function draws when running the model should not change direction. However, if it does, there may be some implicit inclusions of the impact of one or more variables in the formulation of the envisioned relationship. The graphical function must have some elasticity of variables over the range (outside its historical operating range) to allow the model to result in genuine new insight. Example, if the graph shows a relationship that according to a historical trend something happens every 2 cycles, the range for cycles in the specific graphical function should allow for longer or smaller cycles as possible outcomes to observe if the relationship changes patterns.

Shifts in feedback loop dominance can cause systems to generate surprises, and be responsible for the nonlinear responses - large pushes can yield barely discernible reactions, and small tickles can unleash avalanches. These shifts are caused by variation (e.g., implemented by using a graphical function) in the associated parameter values associated with the loops.

Feedback loops can perform in different ways. They can be a reinforcing loop, or a counteracting loop. They both serve to better balance the model and reflect an event; however, a counteracting loop is considered better for increasing control of the dynamic behavior than reinforcing loops. An example for these types of feedback loops are shown in Figure 8.

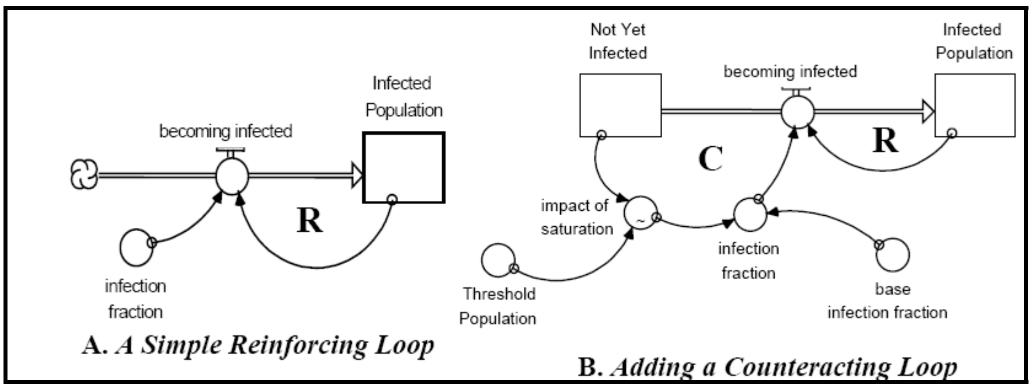


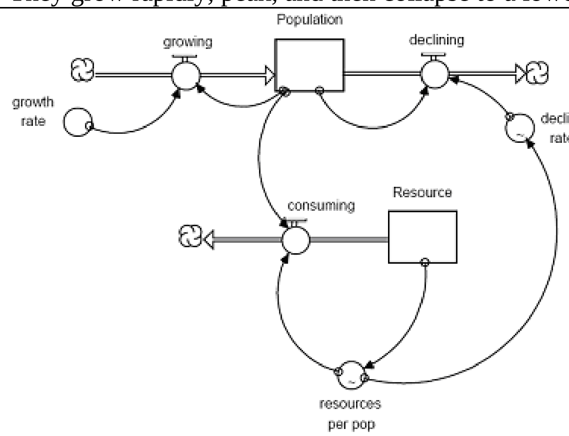
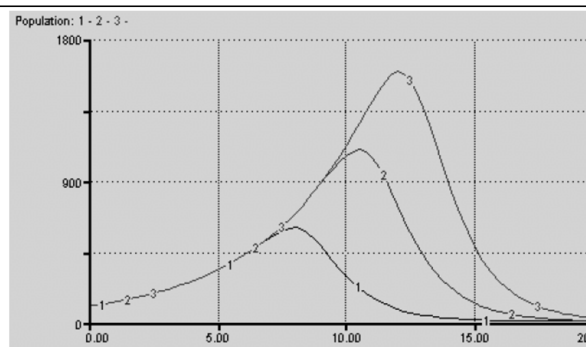
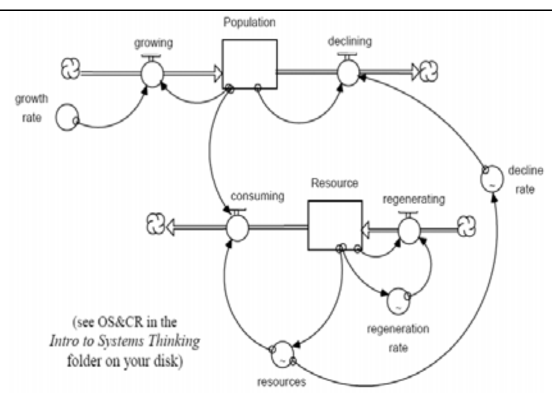
Figure 8 Reinforcing and Counteracting Loop Example
Source: Modified from isee systems (2004).

In summary, the benefits for using feedback loops are they:

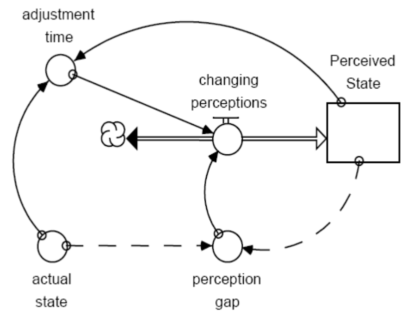
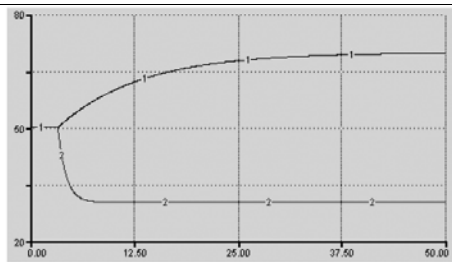
- enable systems to maintain internal balances, and also grow;
- guide evolutionary adaptation, and preside over catastrophic collapses;
- self-generate all manner of dynamic behavior, and set in motion an ongoing dynamic (a more than one-time response);
- relate the strengths of the various feedback loops that make up the system to the dynamic pattern traced, and how those strengths wax and wane over time. The graphical function serving as a coupling point between loops is often the vehicle for enabling such waxing and waning to unfold.

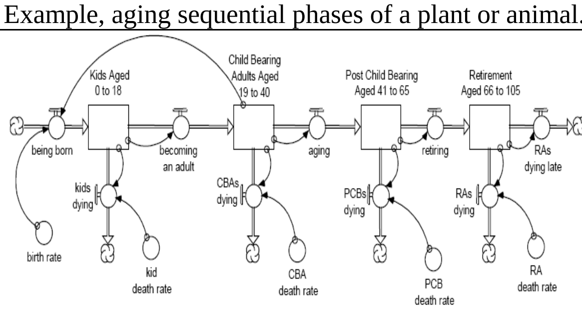
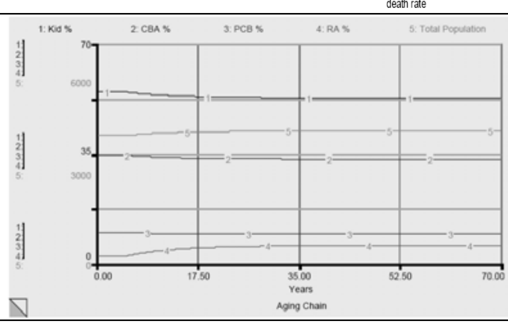
More complex formulations are possible in STELLA software by using one of five different infrastructures templates. The five generic infrastructures can serve as nuclei for constructing models that combine paragraphs and give rise to their own dynamic behavior. The templates for the infrastructures and their respective details are shown in Table 3.

Table 3 Infrastructure Templates Examples in STELLA

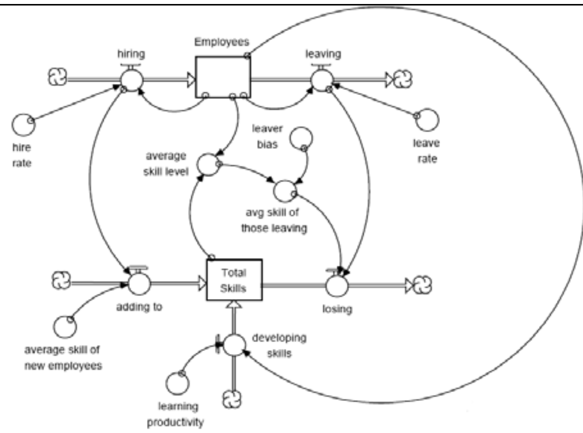
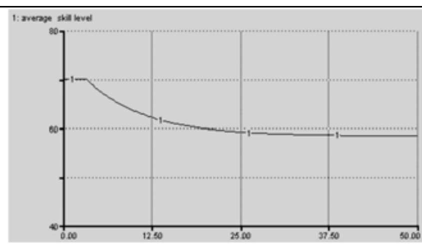
<table>
<tr><td>Template 1</td><td colspan="2">Overshoot and Collapse</td></tr>
<tr><td>When to Use</td><td colspan="2">For physical, biological, and social systems. Transition from growth to steady-state is not smooth. They grow rapidly, peak, and then collapse to a lower steady-state value (e.g., extinction).</td></tr>
<tr><td>Structure Description (example)</td><td>
</td><td>Population consumes a non-renewable resource. Resource scarcity collapse population. No possible recovery.</td></tr>
<tr><td>Dynamic Behavior</td><td>
</td><td>Growth phase of the pattern looks like S-shaped. First growth expands rapidly - resource is abundant, compounding process dominates behavior. Resources drawn down, death rate loop gains strength, growth slows (Population close to maximum value). Population cannot be sustained - Resource continues to decline. Outflow from Population becomes greater than the inflow, and remains. Time is not doubled or tripled before system collapses - compounding processes generate exponential, not linear, growth.</td></tr>
<tr><td>Variations on Generic Theme</td><td>
</td><td>Variation of the generic overshoot and collapse structure – allows resource regeneration which rate declines as the level of the resource declines. This structure can generate a rebound from the collapse under certain situations, but resources per pop must go to zero before Resource reaches zero. Resource = zero, no basis for system regenerating.</td></tr>
</table>

Continuation of Table 3

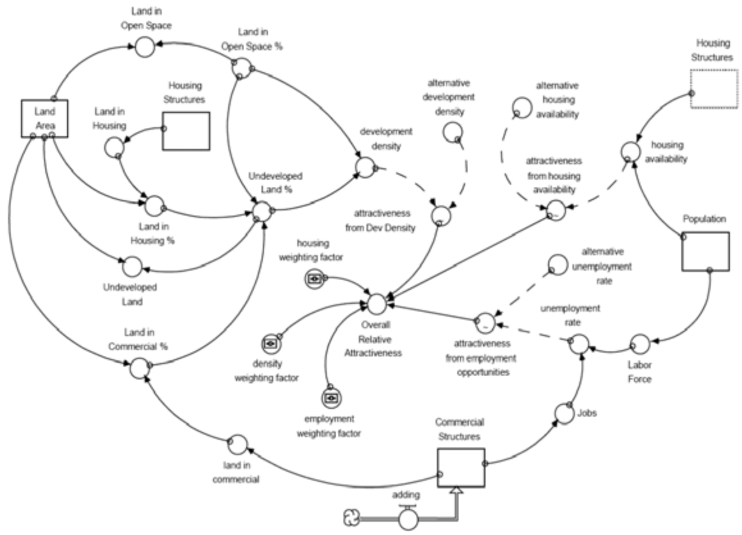
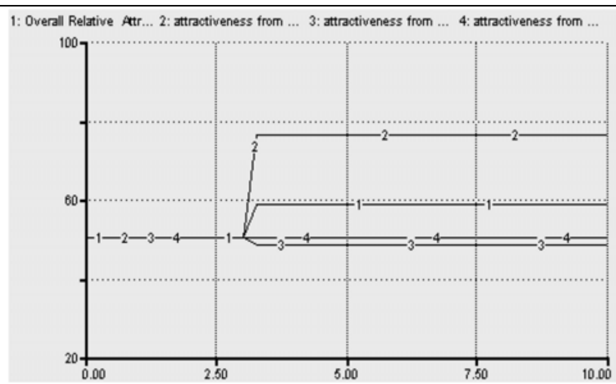
Template 2	***Slippery/ Sticky Perceptions***	
When to Use	Existence of a rate asymmetry, perceptions is adjusted. This structure captures it without needing a lot of technical wizardry (e.g., consumers get aware of a product quality problem).	
Structure Description (example)		A stock-adjustment template with one wrinkle. *Adjustment time* is a variable, not a *constant* - depends on the *Perceived State* and the *actual state* relationship. Actual State < Perceived State = small adjustment time (perception process slippery downward). Actual State > Perceived = large adjustment time (sticky upward adjustment).
Dynamic Behavior		Depicts the response - an initial steady-state, to actual state - 40% step-increase and step-decrease. Responses are not symmetrical. Completed downward adjustment takes few time periods (slippery), while upward adjustment takes nearly 50 time periods (sticky).
Variations on Generic Theme	Allow the adjustment time to be represented by a graphical function, rather than by using an algebra. This enables speed of adjustment to vary more continuously (not only one value if actual is less than perceived, and another value otherwise).	

Template 3	***Main Chain***	
When to Use	Also called spinal cord – useful to represent a sequence of stages through which stuff passes. Example, aging sequential phases of a plant or animal.	
Structure Description (example)		The chain of reservoirs is fed at the front-end by being born single flow. Two outflows drain each reservoir - a flow-through that moves stuff on to the next “phase” (age category), and an exit flow that drains stuff out of the chain. Associated with each exit flow is death rate. All outflows in the chain are represented by the Draining template.
Dynamic Behavior		In steady-state they distribute total contents among the chain stocks in proportion to the each associated stock average residence time, which is determined as some blend of its flow-through and exit time constants.
Variations on Generic Theme	Classic form - Main Chain is fed with an inflow only into the first stock in the chain. Inflows added to any other stock modifies the classic structure. Replacing reservoirs with conveyors is another option; and varying parameters associated with the draining processes (e.g., draining fractions) rather than remaining constant, is also another option.	

Continuation of Table 3

Template 4	***Attribute Tracking***	
When to Use	Used to "track" an attribute associated with a stock. Structure creates an attribute moving exponential average, which gives less weight, progressively, to the further back in time numbers being used in the calculation.	
Structure Description (example)		Attribute being tracked: skill level of a population of employees. Moving average skill level calculation for the overall population (per employee): total number of employees divided into the total amount of skills they possess. Each employee hired carries an average amount of skill (a co-flow process). Each one who leaves (also a co-flow process) carries an average level of skill. The latter amount is related to the current average skill level of the population. The relationship is the multiplication of the average by a *leaver bias.* Bias greater > 1.0, leavers takes something greater than the current average; if = 1.0, leavers take the average; if < 1.0, leavers take less than the average when departing. Other *Total Skills* stock inflow that is *developing skills* occurs independently of flows of employees. *Developing skills* flow formulation is the External Resource process (not always the case).
Dynamic Behavior		Infrastructure initialized in steady-state (hiring = leaving*)*, the *leaver bias* is zero (those leaving are not taking existing employees' average level of skills, despite new employees getting in having lower skill). To system remain in steady-state; it must offset the difference of the employee's population skills through the *developing skills* inflow. The result = existing population slow decay of the average skill level - down to a new, lower steady-state value.
Variations on Generic Theme	Variations on this structure are achieved by varying the parameters associated with the structure. Variations can be driven by the average level of the attribute. Example: *leave rate, leaver bias, learning productivity,* and the *average skill of new employees,* could all be represented as graphical functions of *average skill level*.	

Continuation of Table 3

<table>
<tr><td>Template 5</td><td colspan="2">Relative Attractiveness</td></tr>
<tr><td>When to Use</td><td colspan="2">Useful to generate an index of attractiveness that is comprised of a set of attractiveness components - a weighted average of the components.</td></tr>
<tr><td>Structure Description (example)</td><td>
</td><td>Example: a population center with three attractiveness “factors” attached to sliders, which are chained - 100% of the weight can be distributed.</td></tr>
<tr><td>Dynamic Behavior</td><td>
</td><td>Initialized infrastructure is to generate a relative attractiveness steady-state. Attractiveness components (density of development, unemployment, and housing availability) = to values for each component taken on by the town/city/region to which this population center is being compared. Figure shows, attractiveness increase from employment (2) is somewhat offset by a decrease in attractiveness from the higher development density (3), caused by the increase in business structures numbers. Playing with the weightings and re-simulating the test shows the impact changes.</td></tr>
<tr><td>Variations on Generic Theme</td><td colspan="2">By adding more attractiveness factors and allowing the factors weightings to vary (rather than remain fixed). One apparent human perception process characteristics is that a particular component of attractiveness being satisfied, people tend to weight it less. Based on this notion, weights can be set up to vary (e.g., Maslow’s hierarchy of needs).</td></tr>
</table>

Source: Based on isee systems (2004).

The writing process in STELLA builds on the idea of keeping it simple, while remembering that the model is not reality, it is just a representation to try to account for the phenomena. Writing is good to *learn* despite also sharing one’s thoughts and feelings, entertaining, instructing or informing, and inciting action (isee systems 2004). The steps involved in writing the system model in STELLA are shown in the Figure 9.

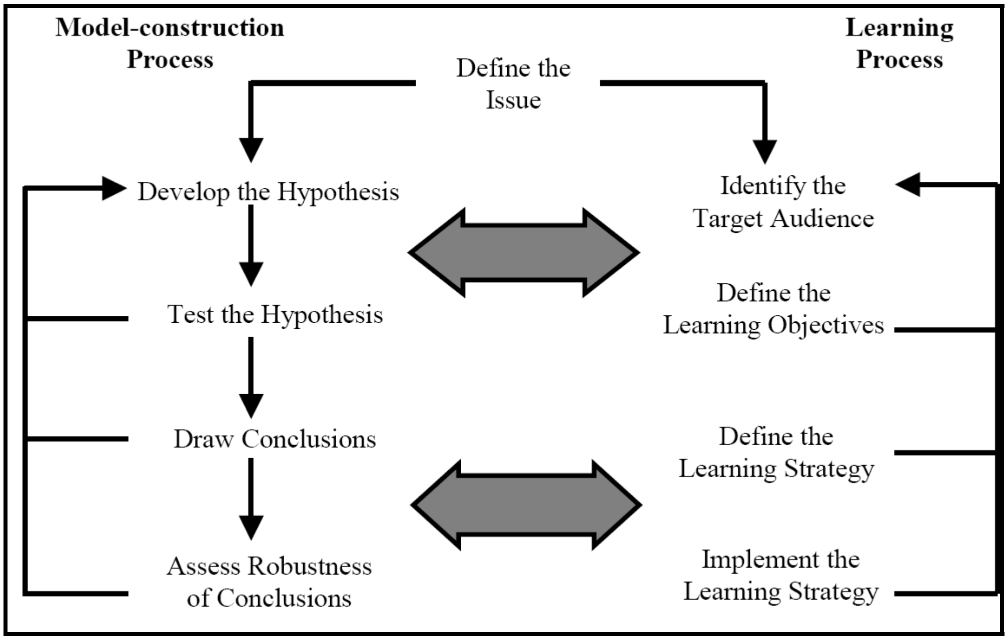


Figure 9 Writing Steps in STELLA
Source: isee systems (2004).

Constructing a model and integrating learning processes into the model should be done in parallel to help make sense of the formulation and ensure a proper representation of the issues. The sequence of steps in both the model construction and learning processes is far from linear. The loop back arrows that represent learning and the large two-headed arrows linking the parallel streams visually reinforce that the streams running are in parallel, have a lot of interplay between them, each informing the other. Therefore, as soon as an issue is identified, the learning process must be developed in parallel with the model development to help the time invested into making sense of the overall context in analysis. To be understood, both processes must be guided by a sharply-focused issue, couched as a dynamic phenomenon.

In other words, there are basically two purposes for STELLA-based modeling efforts – the creation of a research tool, and the creation of a learning tool. A single model can serve both functions, but in practice this rarely occurs. The basic differences between these tools are:

- research tools tend to be answer generators, often with large models, placing value on highly-precise parameter, and generating numerically accurate results;
- learning tools inspire insights, and catalyze changes in the assumptions underlying the mental model using relative (internally-consistent) parameter values (rather than absolute and numerically precise ones).

This means, it is important to follow this sequence when constructing a model (Figure 9). The sequence is:

- define the issue – dynamic thinking;
- develop the hypothesis – 10,000 meter and system as cause thinking;
- test the hypothesis – replicate the dynamic phenomenon, and for verification of model robustness (model in steady state, test one thing at a time to find limitations or when it stops making sense). Robustness tests help building confidence in model formulations and identify high leverage points (big reaction);
- draw conclusions; and
- assess robustness.

For the learning process it is important to follow this sequence:

- identify the target audience;
- define the learning objectives;
- define the learning strategy (passive or active, although STELLA prefers the active strategy – exercising, extending, and thus constructing, and using empathy thinking skills); and
- implement the learning strategy.

In fact, capturing a system feedback in a loop structure in an operational way is the strength of the system dynamics model and is the main difference between building models with tools like spreadsheets versus using the STELLA software.

2.5 The Benefits of Using STELLA

Some of the benefits of using STELLA are:

- the language increases the accuracy and clarity of verbal descriptions, ambiguities diminish, and communication becomes much more efficient and effective;
- the software provides a check on intuition, and a vehicle for building an understanding of why the interactions work or not;
- the tools facilitate putting together in an organized and clear way the qualitative and quantitative approaches present in the CIR-DSS framework; and
- the tool enables easier operation, demonstration, and replication of the CIR-DSS framework, serving as the basis for analyzing different types of infrastructure.

The use of STELLA for the CIR-DSS framework requires several different infrastructure templates to build the full model. The identified templates at present are the Main Chain for the overall CIR-DSS framework, the Attribute Tracking for the overall resilience improvement goal of the infrastructure system, and the Relative Attractiveness for identifying better projects choices to improve infrastructure systems (e.g., maintenance or reconstruction, or new projects according to mitigation strategies).

Chapter 4 describes how STELLA was used to build the CIR-DSS.

2.6 Tools to Assess Impacts

HAZUS-MH is software developed by FEMA to assess the impacts of natural hazards and mitigation strategies. In this application HAZUS-MH serves as a tool to generate the outputs that are used as inputs in the model developed using STELLA. This means that not all options for, or the full capabilities of HAZUS-MH are used. Similarly the methods, models, data, and interface used in HAZUS-MH are not evaluated or critiqued.

Hazard mitigation is an action taken to reduce the destruction and disruption effects in the event of future disasters (FEMA 2004). These efforts often result in better and more cost-effective methods of responding to and recovering from a disaster. Mitigation plans for natural hazards are mandatory for state and local entities to be eligible for FEMA funds under the Disaster Mitigation Act (DMA) enacted by the Congress in 2000 (U.S.A. Congress 2000). Planning for mitigation is intended to help communities identify effective policies, actions and tools to decrease future losses. Hazard mitigation uses on risk assessments to estimate the social and economic impact of hazards on people, buildings, services, facilities and infrastructure. The data inventory used in HAZUS-MH is from national and regional databases such as the United States Census, and can be tailored into more detailed analyses.

The case study focus is on floods using the HAZUS-MH level 1 analyses and existing embedded inventory.

2.7 Overview of HAZUS-MH

The basic hazard mitigation planning process according to FEMA (2004) includes organizing resources, assessing risk, developing a mitigation plan, implementing the plan, and monitoring the progress. HAZUS-MH integrates these phases of mitigation planning by identifying hazards, profiling hazards, inventorying assets, estimating losses, and considering mitigation options. The detail for each HAZUS-MH activity listed is shown in Figure 10.

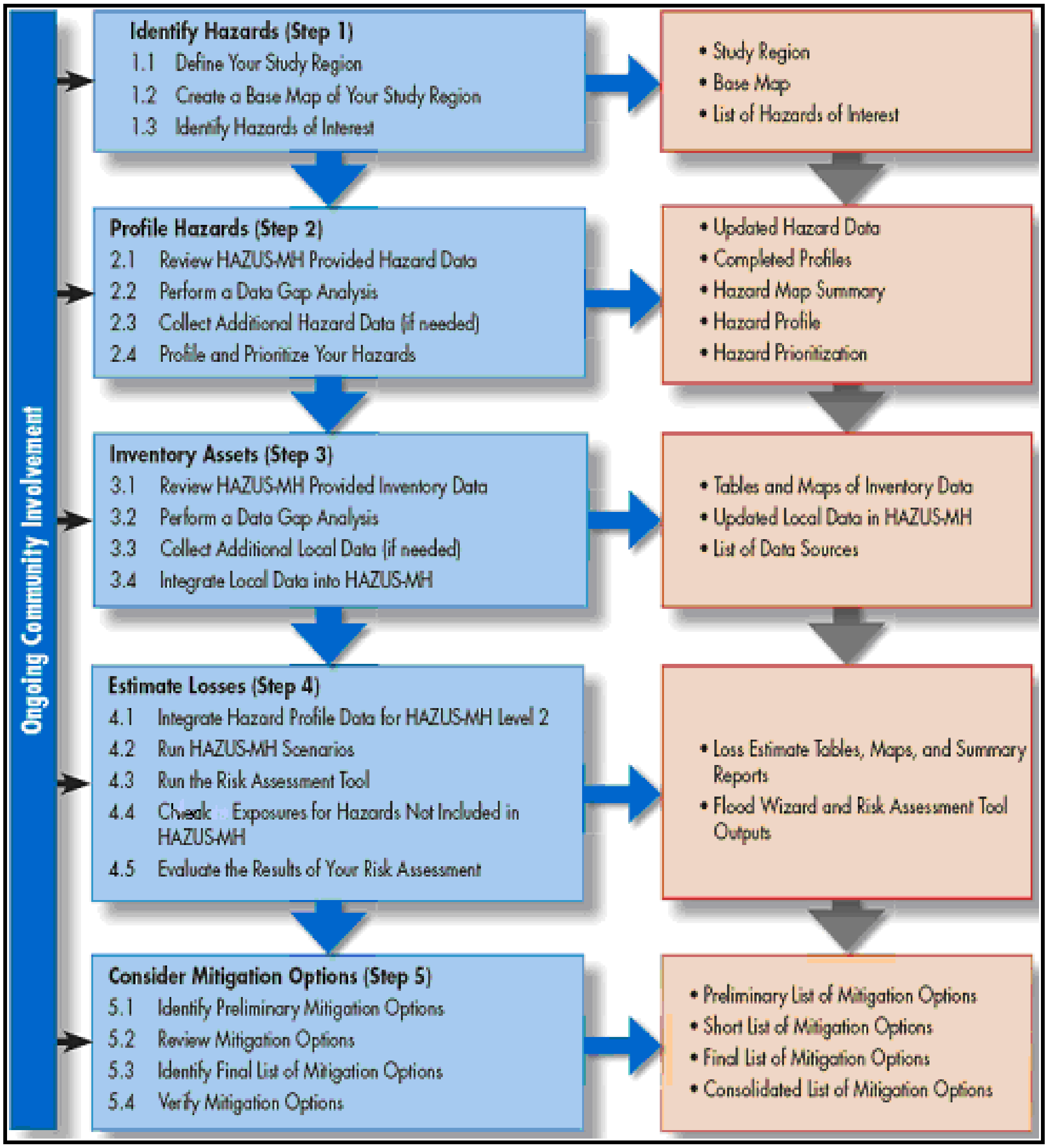


Figure 10 FEMA HAZUS-MH Risk Assessment and Outputs
Source: based on “Using HAZUS-MH for Risk Assessment – How-To Guide” (FEMA 2004).

Suggestions for how to work with HAZUS-MH for mitigation planning include the participation of decision-makers as part of the team to assess risk. In fact in the CIR-DSS framework and in STELLA the decision-makers are included to define what is needed, what they want to have accomplished, and the boundaries and time for such work to be developed.

2.8 <u>Decision Support Systems for Disaster Mitigation</u>

While examples of decision support systems related to infrastructure and disaster preparedness are common, very few examples of decision support systems for disaster mitigation appear in any literature. Two examples are presented here to illustrate the concept. The first "Critical Infrastructure Protection Decision Support System" focuses on the network as a whole rather than an event driven system. The second "Structural Health Monitoring of Bridges for Improving Transportation Security" focuses on project specific technology.

2.8.1 <u>Critical Infrastructure Protection Decision Support System</u>

The model for a Critical Infrastructure Protection Decision Support System (CIP-DSS) was developed to help decision makers understand the consequences of policy and investment options before they implement solutions to highly complex alternatives available for protecting the nation's critical infrastructures. The CIP-DSS consists of holistic analyses of a risk-informed DSS working with 14 critical infrastructures and their primary interdependencies, providing insight for making critical infrastructure protection decisions, since August 2003. The DSS is considered the most effective way to examine tradeoffs between the benefits of risk reduction and the costs of protective action, incorporating "threat information, vulnerability assessments, and disruption consequences in quantitative analyses through advanced modeling and simulation" (DSB 2007; Barton and Stamber 2000; Bush *et al*. 2007). This DSS is useful when helping evaluate and prioritize protection, mitigation, response, recovery strategies; supporting red-team exercises and during crises and real-time emergencies.

The CIP-DSS was developed to fit both inter-regional and intra-urban effect issues, such as incidents involving either localized effects or broad national impacts, using consequence models. Comparison alternatives for infrastructure protection strategies and building consensus among stakeholders in a decision rely on interviews with decision-makers. Case studies were used to demonstrate the project's feasibility proving the approach given by the CIP-DSS concept (Figure 11).

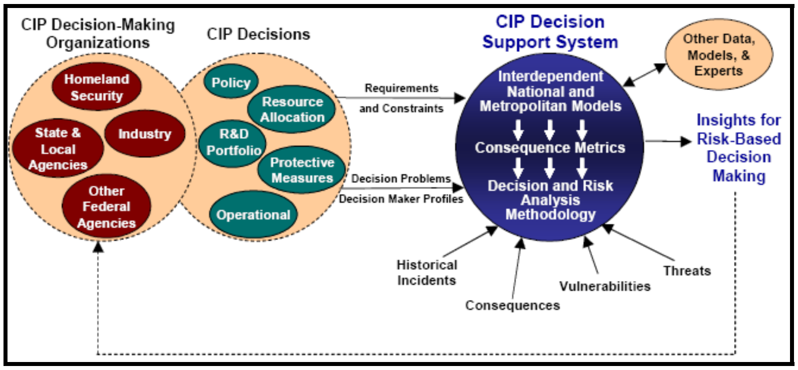


Figure 11 Critical Infrastructure Protection Decision Support System Concept
Source: Bush *et al.* (2007).

As part of this initiative, Sandia National Laboratories "developed an agent-based model for critical U.S. infrastructures using time-dependent Monte Carlo methods and a generic algorithm learning classifier to control decision-making," whose model helps to improve the accuracy of complex system forecasting and provides new insights to deal with emergencies. The computation and analytical results offered new ways of theorizing about the impact of perturbations on an infrastructure network. Agent-based models are further explored in this CIP-DSS research (Barton *et al*. 2000).

More research and model development to work with critical infrastructure decision support is needed to show the many different approaches to types of infrastructure.

2.8.2 Structural Health Monitoring of Bridges for Improving Transportation Security

The model for Structural Health Monitoring of Bridges for Improving Transportation Security (SHM-BITS) was developed to help decision-makers make faster decisions by taking advantage of technological advances (Catbas *et al*. 2006; SAIC 2002). The technological advances include enhanced system designs and information access that are constrained by the lack of guidelines, a knowledge-base on security, and budget constraints. Such constraints make it difficult to achieve a prepared and well-protected transportation system against man-made or natural threats.

The approach presented in the paper uses the application of SHM technology to determine the condition of transportation structures (mainly bridges) to enable efficient management and transportation asset preservation. It includes identifying, localizing, and quantifying damage and deterioration from different sources (e.g. operations, aging, natural hazards, and terrorism). Terrorism impacts infrastructure condition (e.g. loss, deficiency) which in turn impacts the economy and mobility. Threats and related vulnerability direct efforts toward prevention, detection and response to potential terrorist attacks. Ultimately it is a management decision to make security of the transportation system the main goal. The focus is then on bridges as vulnerable transportation structures. The objective in this research is to look at security measures for bridges integrated with SHM for bridge security and safety improvement in post-disaster emergency management. Integration of emergency management and management systems are shown as needed protection for infrastructure and strategies for recovery from terrorist attacks with minimum loss.

Authors claim that "recovery from man-made or natural disasters will be more efficient and effective, with a resilient transportation system" (Catbas *et al*. 2006). The SHM for bridges is presented as an alternative to security management which requires consideration of complementary concepts such as decision making and emergency management, "as critical components of the transportation network" (Catbas *et al*. 2006).

The SHM technology consists of a continuous or intermittent structural monitoring system that can provide real-time "data analysis and reports on the status and security of transportation infrastructure" (Catbas *et al*. 2006). The framework includes the integration of Bridge Health Monitoring for taking advantage of existing tools for determining detours, facilitating evacuation, enabling transportation access to emergency vehicles, and more.

2.9 Applying the Concepts to Resilience of Critical Infrastructure Systems

The complex problem of improving the resilience of critical infrastructure systems challenged by disasters and the continuous operation of these systems involves many aspects of the current social organizations and way of life. Witnessing the dynamics of such systems due to real disasters reveals a high degree of interconnectedness and interdependency among systems. If disturbed or disrupted, these systems can highly impact the Nation’s economy and development. It is important to have resilient infrastructure systems (critical infrastructure systems). This involves increasing our knowledge of such systems through research including concepts and terminology related to resiliency, state-of-the-art research related to system metrics and behavior, technology, developing or improving skills required to establish logic, and straight forward reasoning. A definition, characteristics and metrics for resilience are discussed, and an approach to capturing the resilience of the critical infrastructure system through time is defined. All these factors make this a complex problem.

After presenting the idea of what is involved in this complex problem, it is important to structure the problem to be solved. Because of the nature of the problem, a decision support system was the approach chosen to deal with the critical infrastructure system dynamic. A diagram summarizing the key subsystems and components with information flow and feedback was than developed.

Moving toward testing the CIR-DSS framework represented by the system dynamics diagram, it is time to look at tools that enable development of system dynamics models. The chosen software, STELLA was shown to be a more comprehensive approach including

- the development and/or improvement and use of thinking skills,
- helping to check intuition of critical infrastructure system dynamics behavior,
- aligning model development to learning skills, and
- making it possible to test and replicate the modeling system.

The knowledge required to work with the STELLA software included learning

- the names and function of diagrams (e.g. stocks, flow, connectors, coverters),
- the way these model diagrams can work with each other (e.g. infrastructure templates such as Main Chain or Attribute Tracking),
- how to build feedback mechanisms,

- how to fix the model as it is being developed, helping to identify inconsistencies in calculations as variables are completed with values or equations, and
- how to develop a model's presentation or interface where simulation of scenarios are developed and the model's history (Storytelling) can be presented.

The STELLA software enables building a model as a reconstruction of an event. Input variables in the model are brought in from other applications such as HAZUS-MH from FEMA for impact assessment.

Examples of existing research for addressing mitigation are the CIP-DSS and SHM-BITS. The CIR-DSS framework, however, draws its basic architecture from the Virginia Department of Transportation (VDOT) work Decision Support System for Highway Infrastructure Management (DSS-HIM) (de la Garza *et al.* 1998). The development of the DSS-HIM was to serve as an instrument for guiding highway infrastructure management policy-making, planning, budgeting, and programming, shown in Figure 12.

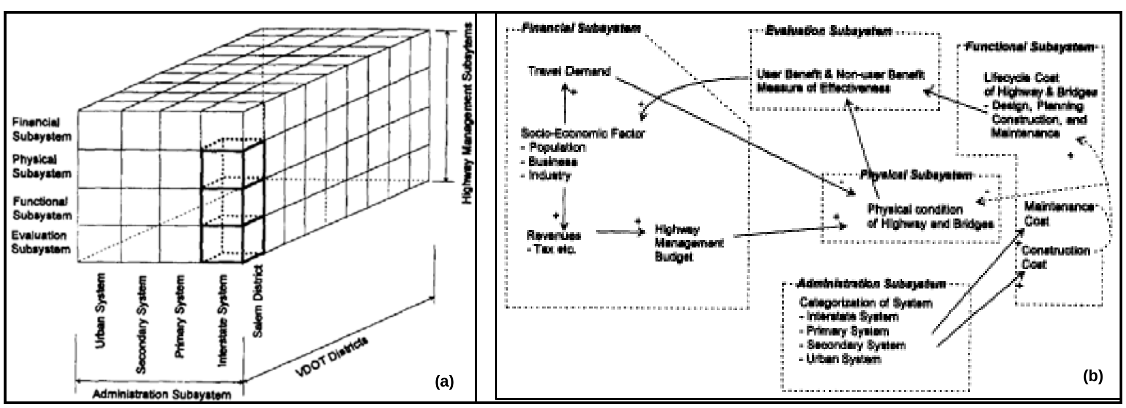


Figure 12 Virginia DOT Decision Support System Concept (a) and System Dynamics Diagram for HMS (b)
Source: Modified from de la Garza *et al.* (1998).

While it is easy to see approaches to mitigation in previous research projects, none of these address resilience directly or propose a way to “read” the resilience of the system. While the literature discusses resilience, there are on-going efforts to address resilience, ranging from the thermodynamics approach (Fiksel 2003) to discussions in sociology of resilient communities (MCEER Earthquake Engineering to Extreme Events 2006; Sarewitz and Pielke Jr. 2002). As the state-of-the-art research in resilience advances, this research addresses this gap by proposing an alternative measure of resilience: a value resulting from condition, performance and disruption values. It also indicates the need to include connectivity as a good measure to add to the resulting resilience value.

When one looks at the complex problem including critical infrastructure and disaster, it is clear that solutions will likely be the sum of many different and complementary approaches. A critical infrastructure system network that must continue to operate/function to be resilient needs to have an adaptive capacity to deal with different stress or loads imposed on the system from time to time. Therefore, there is a clear need for addressing the resilience of systems – a condition to continue and assure life presently and for future generations.

The following section builds upon the use of all this knowledge, applying it to a specific case study. The Decision Support System model uses the CIR-DSS framework approach to lead the way in the analyses for improving resilience of the critical infrastructure system. Resilience is viewed in two different ways. First, as the system behavior in response to the disaster, and second, as critical infrastructure system’s resilience improvement projects through time, assuming that mitigation strategies are including resilience as 100% effective in solving the problem caused by disaster (damage).

CHAPTER 3 A FRAMEWORK FOR A CRITICAL INFRASTRUCTURE RESILIENCE DECISION SUPPORT SYSTEM

3.1 Overview

The framework and conceptual model for the Critical Infrastructure Resilience Decision Support System (CIR-DSS) was developed to address gaps in the existing decision making process. The framework is based on system dynamics to show the interactions between each different component and explore the way the system adapts to feedback. This chapter describes the framework and the process for implementing the framework.

Building on the work "simulating highway infrastructure management policies" of de la Garza *et al*. (1998), the DSS subsystems are:

a) Spatial Decision Support System (SDSS) – GIS & HAZUS,
b) Infrastructure Management System (IMS) – (e.g. FEMA-BCA – benefit-cost analysis principles including projects net present value-NPV, and benefits in terms of avoided damages) for highway asset management (FEMA 2007b),
c) Management Information System (MIS) – based on resilience principles, and
d) Results Presentation System (RPS) – the Critical Infrastructure Resilience Decision Support System (framework) itself.

With these subsystems all three dimensions of the complex problem are covered. First, the inherent chronological dimension is represented in the financial, physical, functional, and evaluation subsystems (for example, the effectiveness of different maintenance policies over the life cycle of the infrastructure). The second is coverage of the different infrastructure subcategories, (e.g. – transportation: highway, bridges, and traffic systems) through an administration subsystem. Third, the spatial interrelationships are viewed through the geographical identification of the location of facilities that can be linked to the likelihood of a particular type of disaster. The CIR-DSS is delimited and applied considering:

- Physical infrastructure conditions (deterioration and maintenance dynamics),
- Functional assessments (life-cycle cost estimation routines), and
- Evaluation of vulnerability and damage assessment within the selected location.

In other words, the analysis consists of the interaction of the three DSS components:

- the GIS/HAZUS-MH - model base,
- the MIS – database composed of the resilience of critical infrastructure systems (RCIS) and FEMA-BCA for insight of better project options considering budget constraints, and
- the RPS – the CIR-DSS report and display base.

System dynamics is a way to represent a sequence of events, a relationship among people and organizations that play major roles, the types of policies that enabled certain actions, and several other things. Recognizing that the critical infrastructure system and disaster are a complex problem, a system dynamics representation is one way to view and better understand this issue (Dhawan 2005; Wikipedia contributors 2008).

The system dynamics diagram, shown on Figure 2, represents the framework for a Critical Infrastructure Resilience Decision Support System. The diagram is developed based on the literature and research presented, focusing on resilience, disasters, the decision support system, and related concepts and principles. The overall objective is improvement in system resilience. The systems dynamics approach captures the cross-disciplinary factors in the critical infrastructure system decision making that inherently strengthen the systems yet are both flexible and adaptable after a disaster (Tierney and Bruneau 2007). Each of the system subsystems requires specific types of information for each component.

The flow of information in this diagram (Figure 2) is represented by the solid arrows. The feedback mechanisms are represented by the dashed arrows. The arrows pointing in two directions represent an exchange of information to complete/reach needed details, or influence each other. The framework, “a qualitative organizing principle for analyzing a system” (Sussman

2000), presents results in a qualitative form for CIR-DSS, and includes some modeling of subsystems with numerical/quantitative or graphical/visual results. For example, vulnerability is measured by a total damage range (in US$), and a vulnerability assessment is mapped in GIS.

The CIR-DSS major subsystems shown in Figure 2 are:

a) the Spatial Decision Support System (SDSS) including the critical infrastructure physical subsystem, the critical infrastructure administration subsystem, geographic dimensions, disaster characterization, and spatial analysis tools;
b) the Critical Infrastructure Management System including the functional subsystem of asset management, the financial subsystem, and the Decision Making subsystem. The institutional subsystem is critical infrastructure decision-making organizations and their fields of activity such as policy, resource allocation, R&D portfolio, protective measures, and operations;
c) the Resilience Management Information System including decision support information – a knowledge base, the time frame and post disaster phase activity characterization toward system resilience; and
d) the Result Presentation System including the review of the decision problems-requirements-constraints, the CIR decision support metrics-analysis-parameters, and the result-insight for system resilience improvement. In other words, this result presentation system includes a resilience evaluation subsystem result. The anticipated results are
    - savings with comparatively less damage of infrastructure systems with improved resilience when considering standard projects versus improved projects,
    - extended infrastructure system life-cycle, and/or maintenance-cycles, and

- higher benefit-cost ratios for improvement projects when compared to standard infrastructure rebuilding projects (same as original design).

e) the result presentation system can thus be summarized and communicated using slide presentation and reports.

The subsystems, broken into similar element groups presented in Figure 2, cover three complex problem dimensions (de la Garza *et al*. 1998).

1) An inherent chronological representation of the financial, physical, functional and evaluation subsystems responsible for infrastructure system maintenance policies related to routine effectiveness measurement,
2) An administrative subsystem related to critical infrastructure type subcategories (in transportation including highway/roads, bridges, traffic, and transportation facilities),
3) A geographical characterization/classification of location and the likelihood of a particular type of disaster at that location including the extent, severity, and intensity of the event (that subjects the critical infrastructure to a risk of failure).

3.2 Developing the Framework

A step by step application of the framework is as follows:

First, choose which critical infrastructure system to focus the analysis on. Define and characterize a study area thus identifying the hazard types according to a disaster likelihood map or according to some parameter that justifies such an option.

The second step, diagnose the problem based on the infrastructure condition before the event and the potential hazard. The diagnosis includes doing a vulnerability assessment, an impact assessment, a damage assessment, and developing initial insights regarding potential mitigation strategies focused on improving the of resilience of the system.

The third step, compare the pre- and post-event function, including the parameters related to the physical and administrative subsystems of the critical infrastructure system based on condition.

The fourth step, use the financial subsystem to identify the needed resources to support normal operation.

The fifth step, consider the disaster impact and forecast/real resources required to recover and mitigate a damaged critical infrastructure in specific sites.

The sixth step, consider all decision-makers and the decision factors that define the work and project scope to restore the critical infrastructure system and enhance resilience.

The seventh step, review the complex-system problem, constraints, and requirements to improve systems resilience, complete-redo-adjust the data and analysis to get a better result. For example, the complete-redo-adjust the data and analysis will be considered in cases that need complete data, and that need to use other parameters and threshold values to address different scenarios. Using this step, evaluate alternative project approaches to reach the most effective critical infrastructure system resilience result, in the recovery and the mitigation strategy. In this seventh step the early insights into the effectiveness of mitigation must direct the approaches. Alternative approaches are discussed later.

The eighth step, evaluate and communicate results according to well defined parameters for benefits, effectiveness, consequence, methodology, and complementary data approach techniques. In this step the evaluation and resulting communication include the presentation of options, alternatives, and defined actions to improve the resilience of critical infrastructure systems.

These eight steps serve as a strategy for applying the framework. The sources of data and information that fit this framework differ in format for different subsystems, concepts, condition, and performance measurements. The data vary in spatial parameters, different metrics and rating systems. For example, the physical infrastructure condition requires a deterioration rate (given by the Department of Transportation or calculated). The maintenance cycle can be measured in months or years using several physical condition evaluation parameters that are represented numerically.

It is important to understand that while a quantitative approach to deal with interdependent critical infrastructure usually gives optimum solutions (Lee *et al*. 2006); the qualitative approach integrating quantitative outputs enables representation of the decision-makers role and their decision in opting for a solution that is closer to reality. A CIR-DSS model enables us to consider solutions that go beyond critical infrastructure physical solutions; and enables us to consider solutions that impact society and the economy after a disaster. To obtain a resilient system, trade-offs analysis of infrastructure performance looking at different project options, design improvement, insight to policies, and institutional capability improvement are considered, as well as changing the position of resilience parameters during the infrastructure project selection analysis.

The interpretation of results coming from the CIR-DSS is in terms of safety, operation, function, and performance metrics. This means that each result needs a value and a corresponding threshold to determine the level of improvement targeted.

3.3 Validating and Implementing the CIR-DSS Framework

The validation of a CIR-DSS framework comes from the application of the framework to case studies. The application must reveal a capability of showing the relevant issues and results that support decision-making in laboratory experiences and real-world complex problems. Field studies inherent lack of experimental control, used as an exploratory case study base, is an appropriate approach to imitate systems behavior and get ideas about ways to build solutions (Quarantelli 1997). An application of the CIR-DSS framework was initiated for the Seaford, Delaware flood of June 2006, focusing on the transportation critical infrastructure and using real data and laboratory inputs, which served as validation for the developed framework.

The context of the event, the Seaford region and city economic and geographical features, the transportation infrastructure general characteristics, an initial vulnerability assessment, elevation profile, and flood history were researched, including the use of GIS ArcInfo. Specific details of the roads and bridges conditions, the performance pre- and post-disaster, a damage assessment, an impact assessment, the integration of asset management principles, and an approach to recovery and mitigation strategies analyses were developed using STELLA software from isee systems Inc. The evaluation and validation of the CIR-DSS framework happens through the development of the model, by using a Sensitivity Analysis, and by simulating different scenarios using STELLA's interface functions specially customized to fit the model, confirming that the observed system performance reveals an expected and logical behavior. The communication of results includes a summary of results obtained with the analysis developed including maps, tables, graphs accompanied by explanations. The expected impact of adopting a CIR-DSS is part of the evaluation and validation of the CIR-DSS framework. The contributions and limitation of this approach will be highlighted later in this dissertation.

Disaster affects critical infrastructure systems in a dynamic way. To understand this dynamic it is important to identify the elements that are involved and how they relate to each other. System dynamics is a way to represent the sequence of events, the relationship among people and organizations that play major roles, the types of policies that enabled certain actions, and several other things. Recognizing that the critical infrastructure system and disaster are a complex problem, a systems dynamics representation is one way to view and better understand this issue.

CHAPTER 4 A CASE STUDY – JUNE 2006 FLOOD IN SEAFORD, DELAWARE

4.1 Introduction

To validate the CIR-DSS framework and illustrate the insights that can be gained from implementing the system dynamics models, the framework is applied to a specific event and location. The actual implementation is not intended to be generalized but to show how the concepts can be implemented. This Chapter 4 describes the location and event, and then Chapter 5 reviews the implementation.

4.2 Case Study Overview

On Sunday, June 25th, 2006, the Seaford area of Delaware was flooded. Some areas received over 12 inches of rain. Road and bridge infrastructures suffered serious damage and destruction, impacting evacuation alternatives, and making it difficult to respond to the disaster. This case study focuses on the June 2006 flood in Seaford, Delaware and its impact on the critical transportation infrastructure. The case study uses both real data and laboratory inputs. Newspaper articles, government reports and data available to the public provide the context of the event, regional economic and geographical features, transportation characteristics, an initial vulnerability assessment, an elevation profile, and flood history.

4.3 Background

The Seaford Area is located in Sussex County, in the southern part of the State of Delaware (Figure 13). At that time Delaware had a current estimated population of 853,476 (U.S. Census Bureau 2007b). The 2005 Seaford Micropolitan Statistical Area population, a subset area of Delaware, was estimated at 176,548 (U.S. Census Bureau 2006). The city of Seaford population (a subset of the Micropolitan area), according to the 2006 Census Bureau estimate was 7,080 (U.S. Census 2007a), making it the largest city in Sussex county. The city of Seaford is located along the Nanticoke River in western Sussex County, on the Atlantic Coastal Plain (Guy 2007).

The Seaford area is characterized as a region with a predominant agriculture and tourism economy (Rupri 2006; Falk and Gerner 2004). Seaford City's main industries are medical services, education, manufacturing, and retail (Guy 2007).

Seaford's weather is a mild subtropical climate consisting of hot, humid summers and mild winters, moderated by the Atlantic Ocean. The summer average high temperature is 87°F (30.6°C) and a low is 65°F (18.3°C). During winter, the average high is 44°F (6.7°C) and the average low of 25°F (-3.9°C) (Wikipedia contributors 2006; Weather Underground 2010). This temperature range also gives insight to the types of stress imposed on the critical transportation infrastructure, reflects the types of deterioration, maintenance, investment and decisions in asset management. For example, hurricane season in the U.S. starts in June and ends in November, with the peak season being between August and September (About 2007). This means the highest risk of hurricanes and consequent flood occurs during U.S. summer and beginning of fall. In consequence, the risk of damage to civil infrastructure systems such as transportation systems increases along with the higher chances a hurricane or flood can occur.

US Route 13 is the main north-south corridor that passes through the city connecting Seaford with Bridgeville, Delaware to the north and Laurel, Delaware to the south as part of the Sussex Highway. The Delaware State Route 20 is the main east-west road connecting Seaford with Millsboro, Delaware to the east and Reliance, Maryland to the west. Figure 13 shows US Route 13 and DE State Route 20 in the Seaford area.

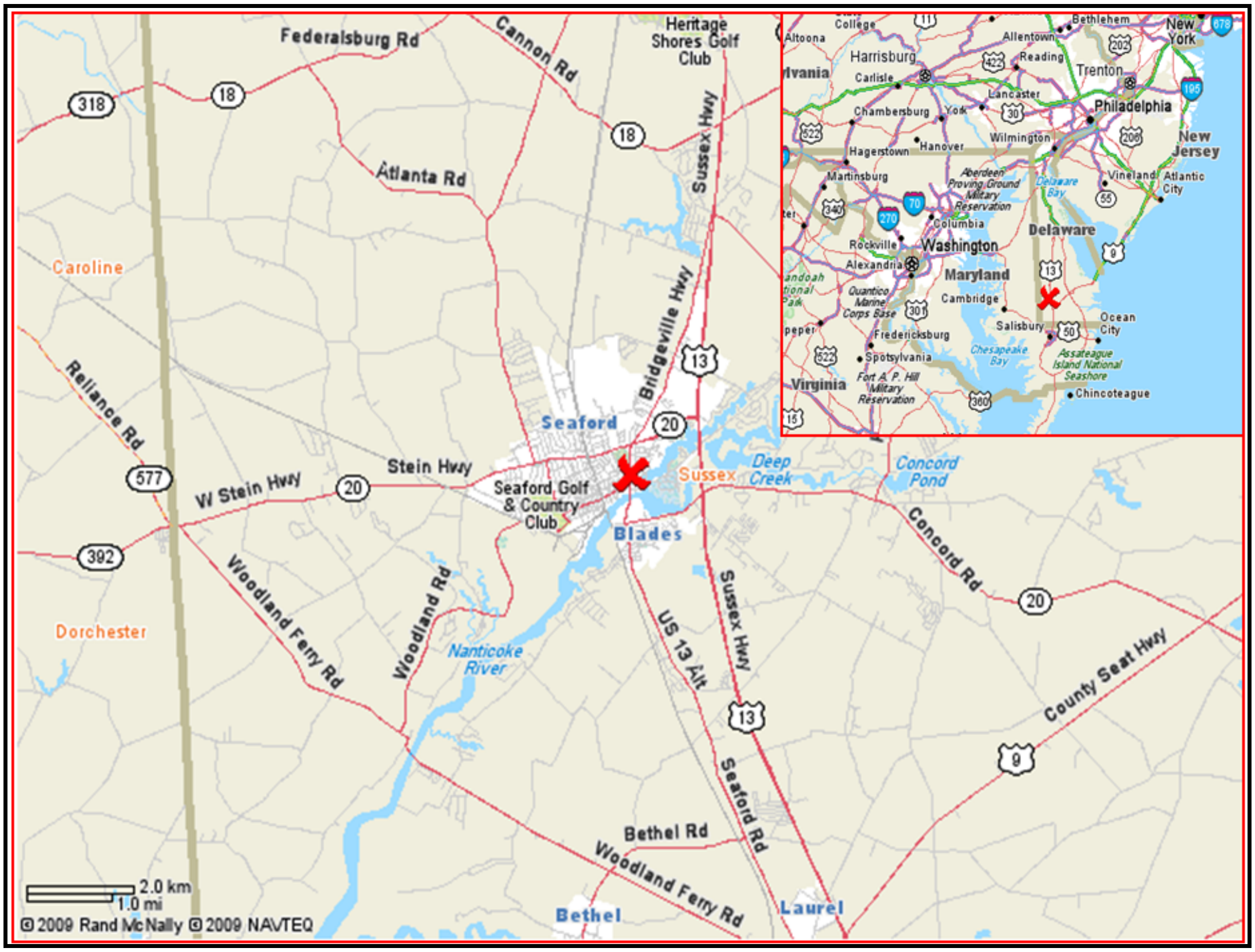


Figure 13 Seaford Area Main Routes
Source: modified from McNally (2007).

Seaford's geographic location is 38.641^{0}N and -75.611^{0}W (ePodunk 2007). Seaford's elevation ranges between 8 to 30 feet (The City of Seaford 2007). An elevation profile of Seaford helps to develop a vulnerability assessment. This area elevation profile is shown in Figure 14.

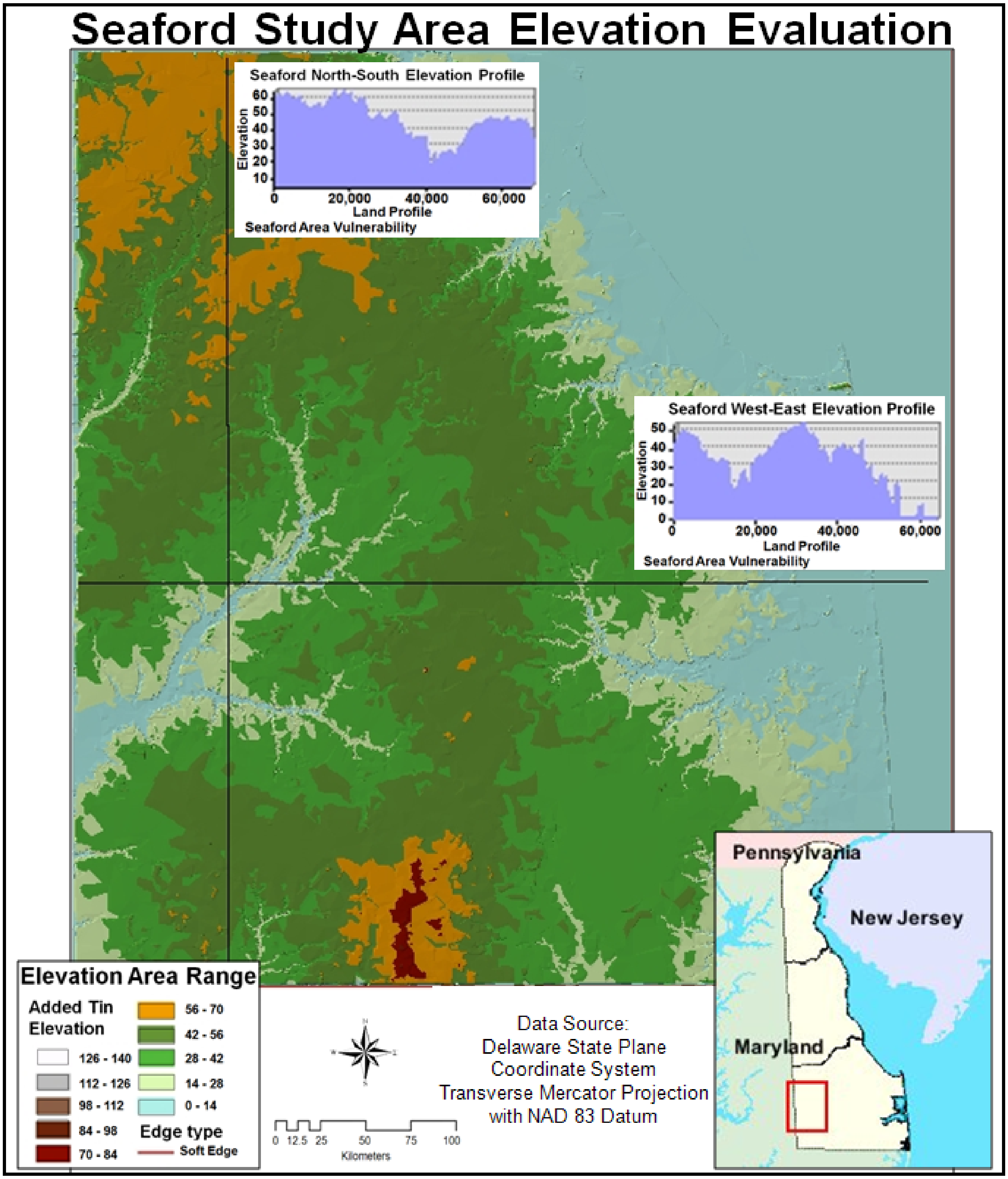


Figure 14 Seaford Area Elevation and Elevation Profile along Black Lines

Source: Developed using ArcInfo GIS.

4.4 Critical Transportation Infrastructure Features in the Seaford-DE Area

To identify the critical transportation infrastructure in the Seaford area, transportation infrastructure data was researched as well as data from the Delaware Department of Transportation (DelDOT) and other agencies. These relevant data include:

- A Seaford, Delaware geographical area delimiting the boundaries for the analysis of the road network. This includes neighboring areas of Maryland as these roads are available for diversion of traffic in the case of flooding that would cause transportation service disruption,
- road and bridges network data for the specific study area,
- main road traffic volume, level-of-service (LOS), and capacity,
- intersections with traffic monitoring systems (cameras and/or sensors for the networked system),
- infrastructure affected by the flood and an areal view of direct infrastructure disruption,
- isolated areas due to flood and transportation disruption,
- infrastructure damage with spatial extent, temporary flood paths and no damage condition, different road and bridge levels of damage and need for repair or replacement,
- other related geographical areas affected, possible interconnected infrastructure of power lines, gas and telephone cables compromised,
- compromised street/road and bridge pre-condition/performance assessment data before and after flood for road network system resilience purpose,
- historical record of actions taken during the flood to show the evolution of flood damage and coordinated work to understand the evolution of infrastructure impact and more vulnerable fields. Used also to help define priorities of repair, reconstruction or replacement of infrastructure projects. For example the coordinated work overview consists of setting up detours;

using available technology at DelDOT/TMC; and mobilizing community (public works, fire fighters, traffic operators, management, DEMA state of alert, others), and

- post-flood assessment and official news presented to public.

The Seaford area two main roads, as mentioned before, are US Route 13 and DE State Route 20. The Seaford area road infrastructure traffic flow, road condition and performance values are included in the model development working paper (Croope 2010a). The estimated daily traffic traveling the main roads and freight movement percentage add to the analysis by highlighting the impact on the economy and on society resulting in longer travel times and increased trip costs.

4.5 Data Sources

The data required for a CIR-DSS is extensive and requires data in good quality, at an appropriate level of detail (scale), in a useful and useable format, and meeting defined standards for collection, access, and storage. The infrastructure data must have a common geographical referencing system to ensure compatibility. Examples of the sources of data available for Delaware are:

- Delaware Department of Transportation (DelDOT) Transportation Management Center pictures, traffic and detours reports (DelDOT Officials)
- DelDOT Bridge Management bridge data (GIS), reports of local damaged bridges, digital maps (pdf) (DelDOT Officials)
- DelDOT (others) roads, state boundaries
- University of Delaware Spat Lab elevation data (http://www.deos.udel.edu)
- Delaware DataMIL roads, rivers, hydrology, municipal boundaries (http://datamil.delaware.gov)
- Delaware Environmental Observing System (DEOS) radar derived rainfall (http://www.deos.udel.edu)

4.6 Model Inputs

To implement the CIR-DSS framework, inputs to the system dynamics model is generated using the Geographical Information System (GIS) tools and HAZUS-MH MR-3 (FEMA 2007e) tools to assess the impact of hazards. These inputs are used to describe the overall resilience of an infrastructure system. The system is then analyzed using systems dynamics. This section describes the input generated in GIS and HAZUS-MS to STELLA.

The analysis developed in GIS and HAZUS-MH is not repeated in STELLA. GIS and HAZUS-MH are used to generate maps for vulnerability assessment and estimate exposure. A Level 1 analysis in HAZUS-MH organizes and structures relevant data. The results from the GIS and HAZUS-MS are fully documented in the working paper “Working with HAZUS-MH” (Croope 2009). For completeness, brief summaries are included here.

4.6.1 GIS Data

The GIS analysis begins with a map of the study area (Figure 13) and the more detailed map shown in Figure 15. This is supplemented with elevation data (Figure 14) and rainfall data (Figure 16). There are also paper maps, such as a map of detours obtained from Delaware Department of Transportation. The DelDOT-TMC detour paper map (scanned and used as an overlay or digitized) shown in Figure 17 is used to analyze the road as a routable network for the case study area, building detours that can be used to reroute traffic from flooded roads, test connectivity and dependency among different hierarchy roads.

Using this raw data, a map of impacted facilities was developed (Figure 18). Considering the impacted facilities and the network model, an analysis of detour routes was conducted (Figure 19). Major problems using existing data in 2006 to simulate detours set up by DelDOT according to their map shown in Figure 17 and the objective of helping support decision making was imperfect built road network connectivity. This problem was easily seen by roads on map showing different colors, the green roads part of the network, and red roads not part of the network. Detours were built by manually selecting impedances on the road network and making the system find the shortest path between randomly defined locations for origin to destination. The network analysis used all hierarchy roads available and did not consider number of lanes or the direction of roads to set up the paths.

Finally, the location of damaged infrastructure is identified and supplemental information in the form of photographs is provided (Figure 20).

These data were scaled (focusing just on roads) and used as input to HAZUS-MH and later in STELLA.

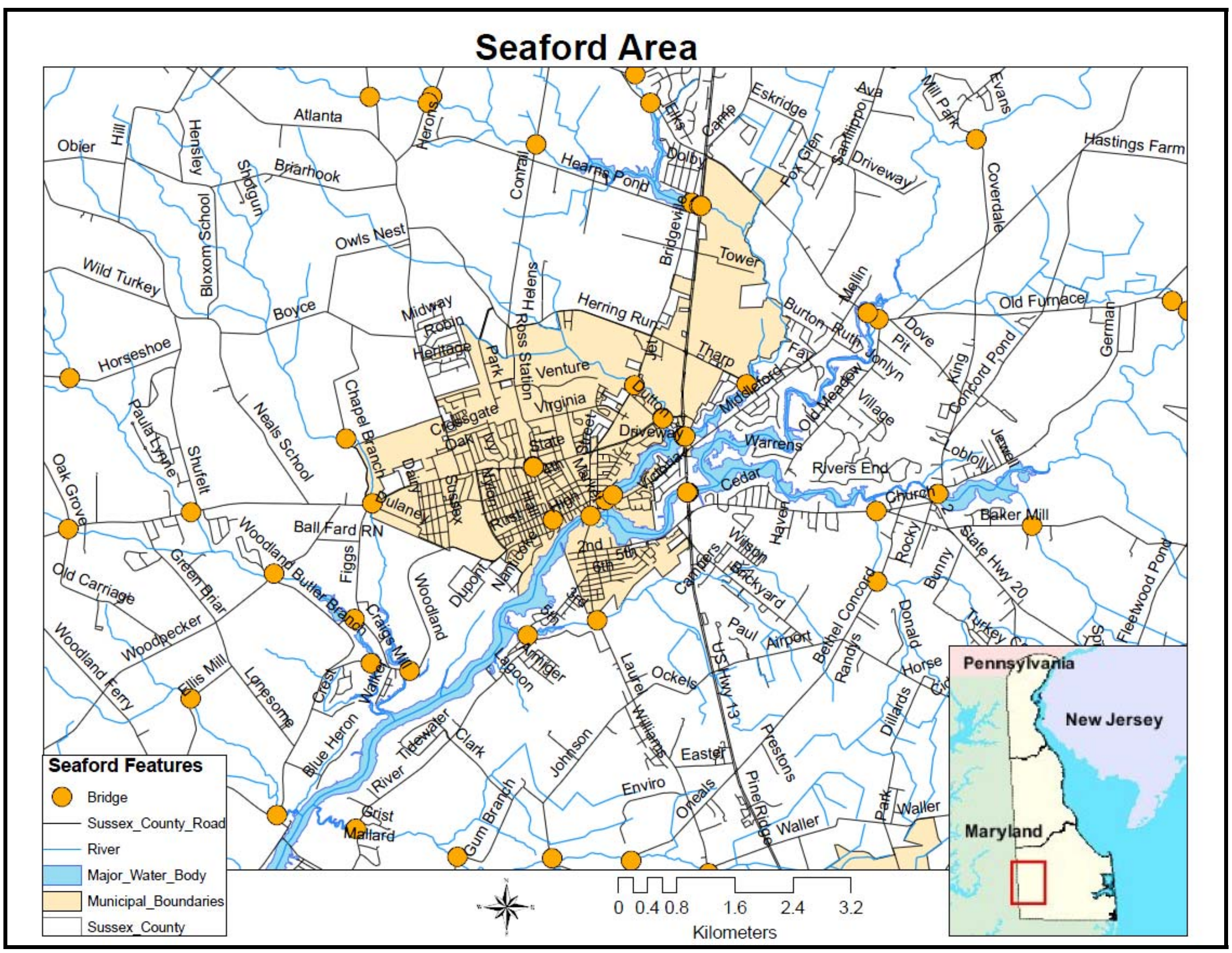


Figure 15 Seaford Study Area
Source: Developed using ArcInfo GIS.

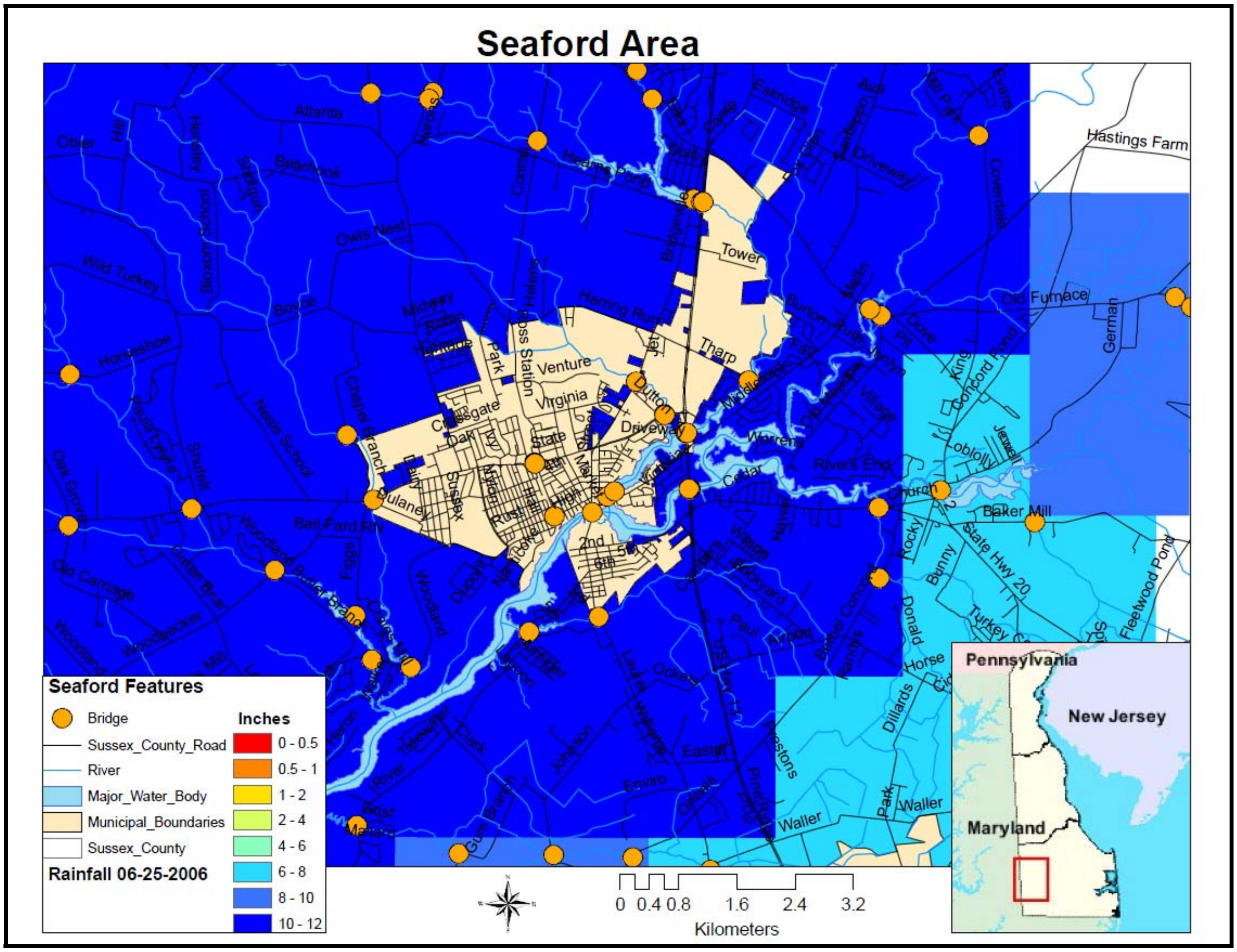


Figure 16 Rainfall in the Seaford Area, June 2006
Source: Developed using ArcInfo GIS.

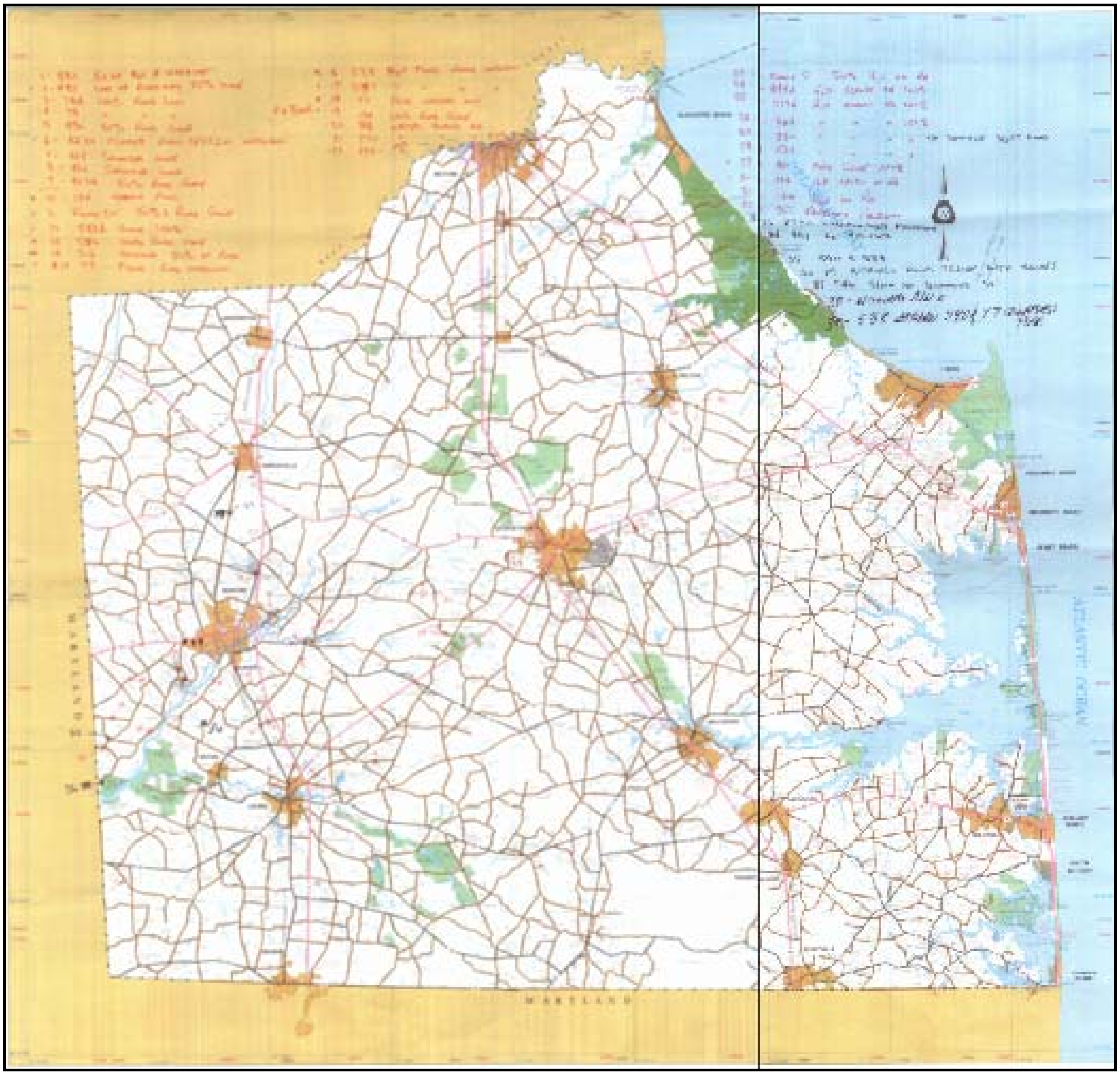


Figure 17 DelDOT Paper Map for Detours Set Up During the Flood of June 2006
Source: Delaware Department of Transportation (2006).

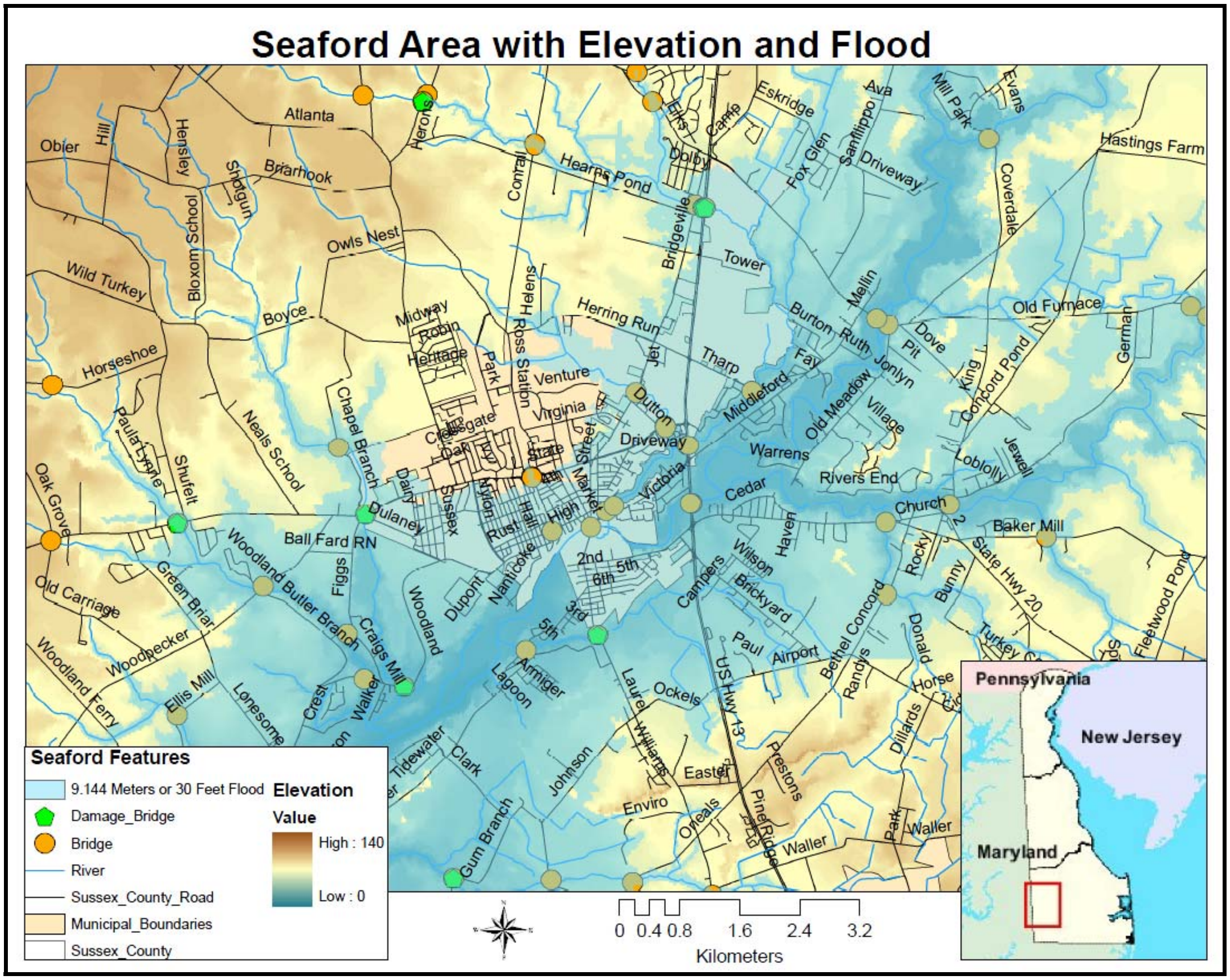


Figure 18 GIS Analysis Results for Seaford Transportation Infrastructure
Source: Developed using ArcInfo GIS.

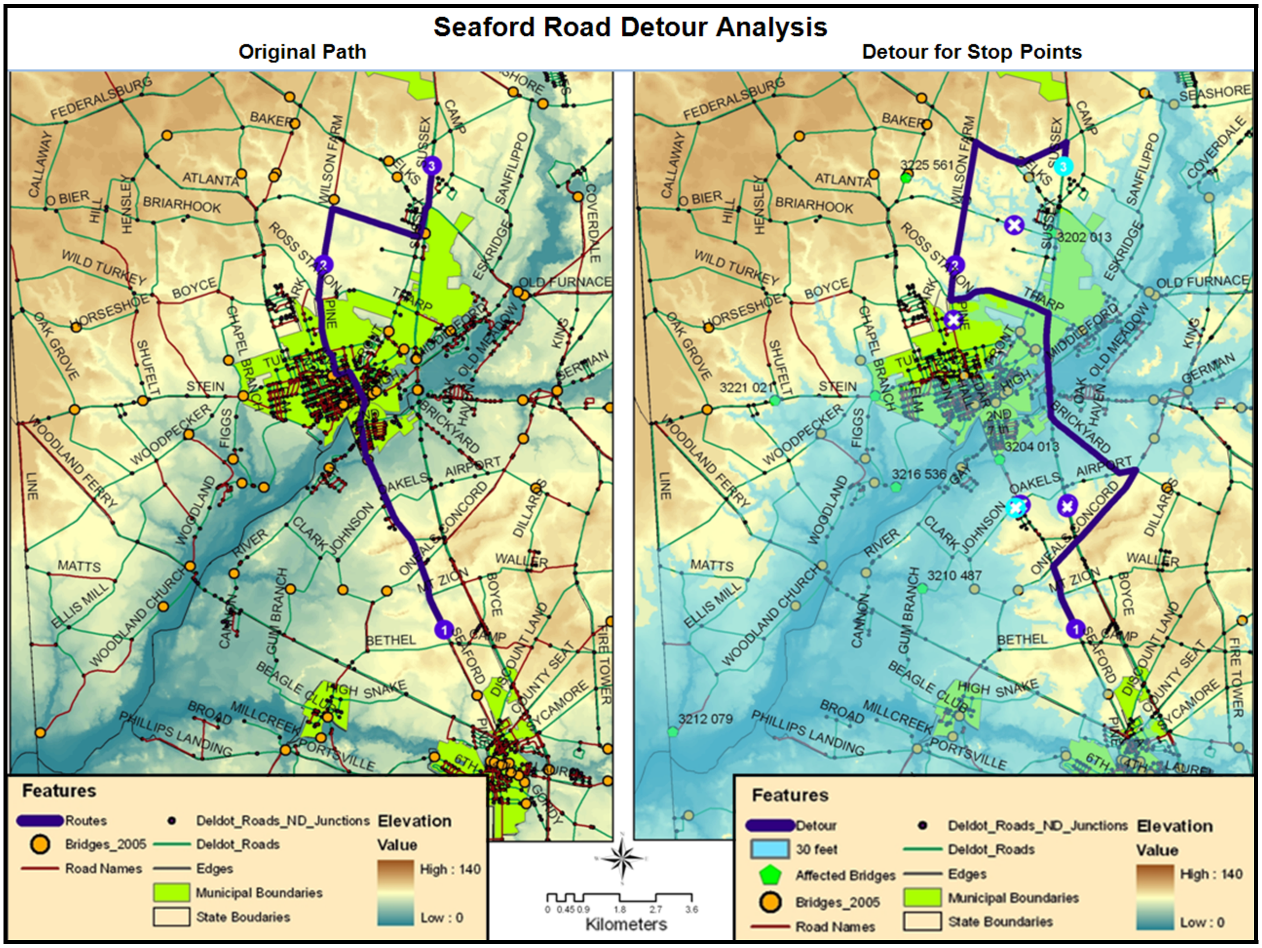


Figure 19 Detour Analysis
Source: Developed using ArcInfo GIS.

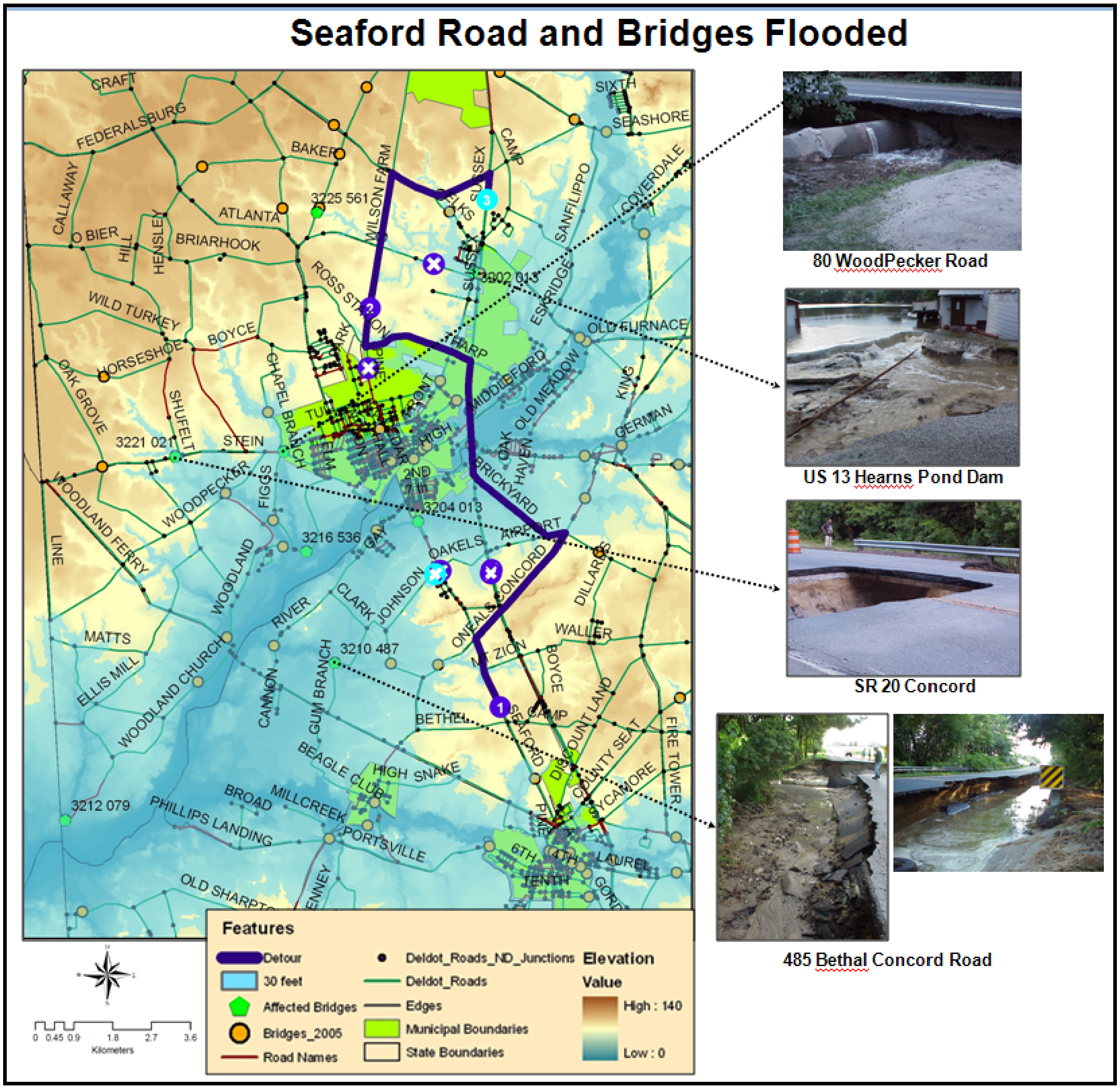


Figure 20 Location of Damaged Infrastructure
Source: Developed using ArcInfo GIS.

4.6.2 <u>HAZUS-MH Results</u>

The results of the analysis in HAZUS-MH include maps, tables and reports that help to organize all existing output. The base map (Figure 21) draws from the maps developed in GIS and scaled to enable faster analysis processing by the HAZUS-MH software. The HAZUS-MH produces maps and data that serve as input for the decision making process. For example, Figure

22 shows impacted area or “Annual Losses” based on a 10-year storm as a standard output although the analysis uses a 100-year storm event, which is better reflected in the earlier images generated by a GIS analysis prior to using the HAZUS-MH software.

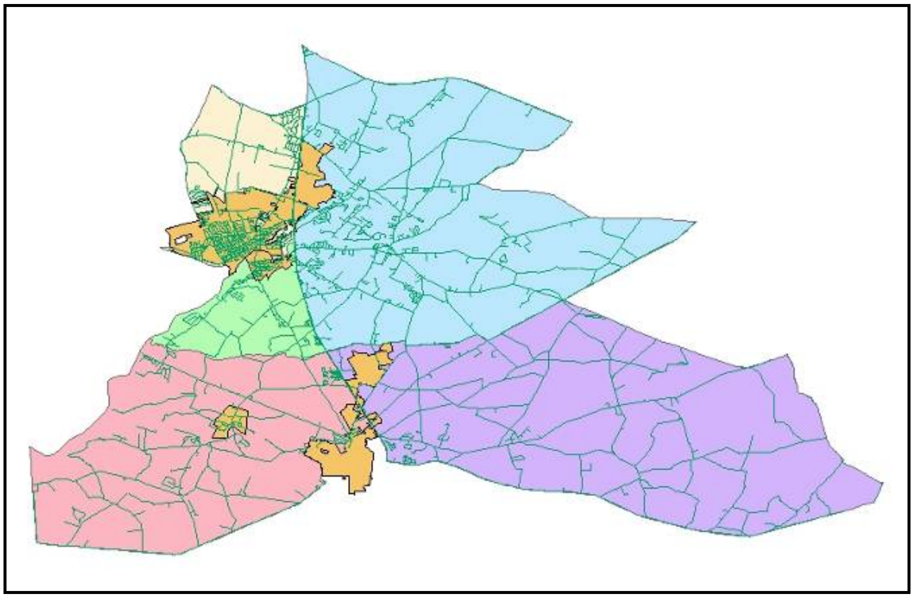


Figure 21 Base Map Built in HAZUS-MH for the Seaford Area
Source: Developed using HAZUS-MH MR-3 (Croope 2009).

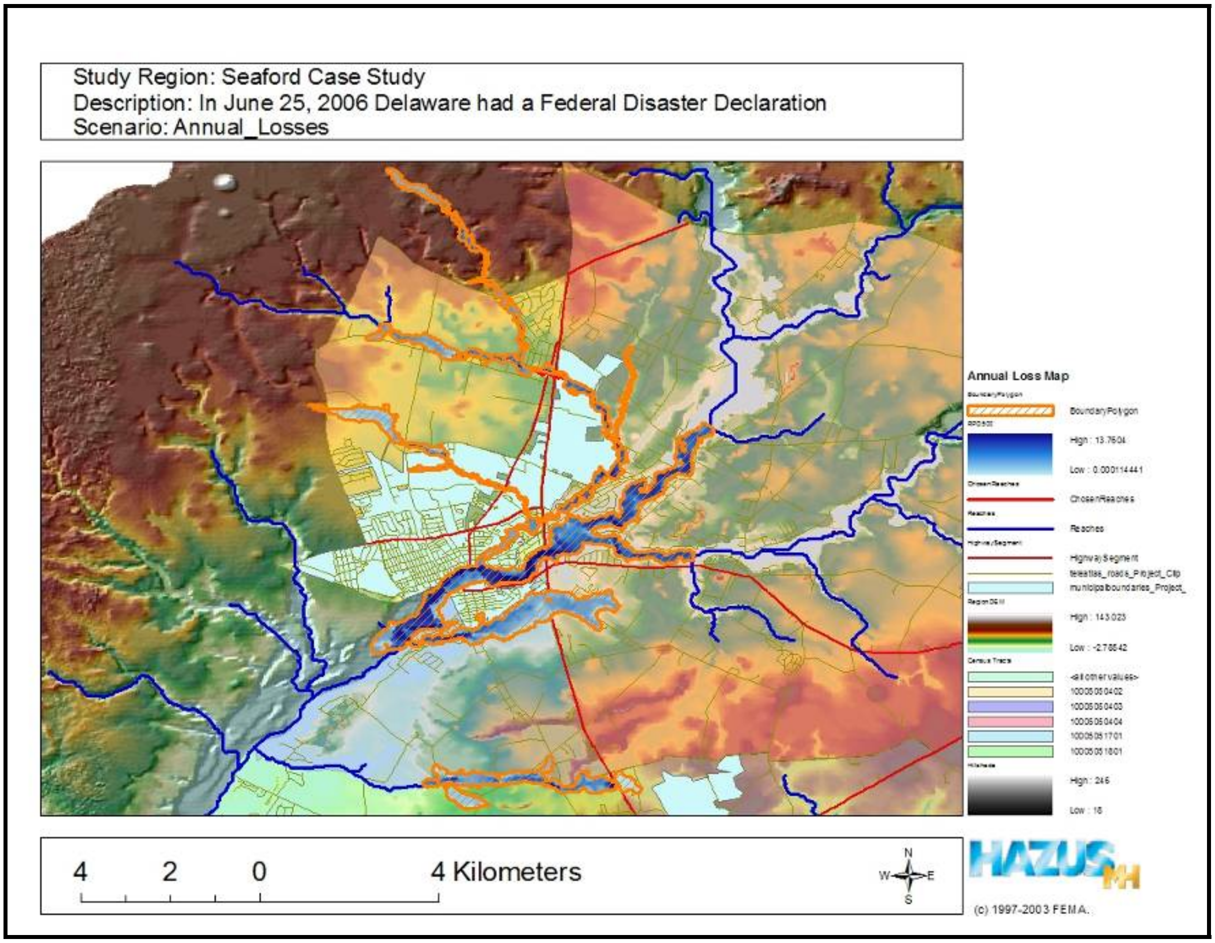


Figure 22 Seaford Area Annual Losses Map of Depth
Source: Developed using HAZUS-MH MR-3 (Croope 2009).

HAZUS-MH includes tools for demonstrating the impact of various strategies (maps and data). For example, Figure 23 shows the impact of adding a levee. Other “What If” scenarios can be generated for flow regulation and the impact assessed in terms of depth of flooding and floodwater velocity.

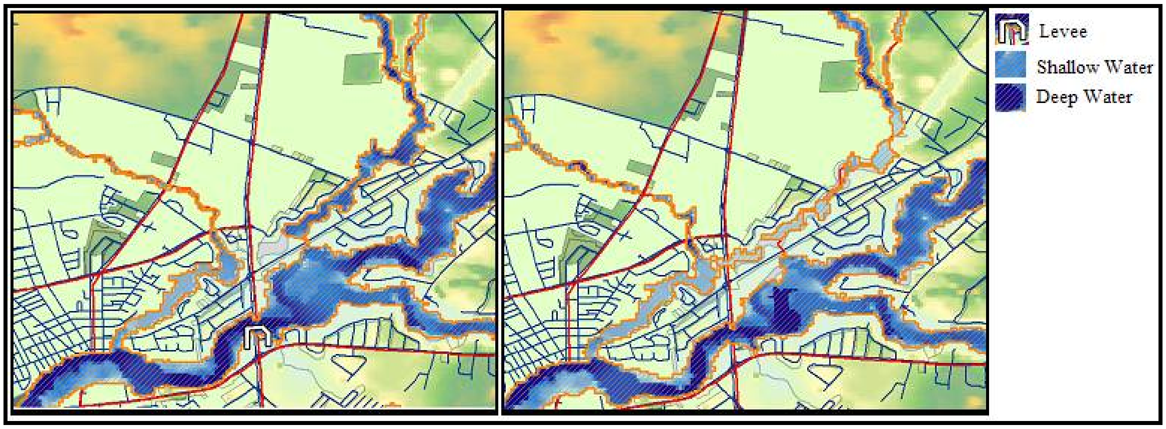


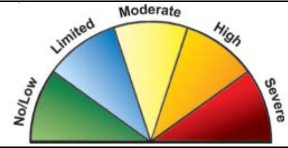
Figure 23 "What if" Levee Protection Scenario
Source: Developed using HAZUS-MH MR-3 (Croope 2009).

HAZUS-MH includes the ability to also include photographs and other media (Figure 24).

Figure 24 Damage related to US13 in Sussex County
Source: Image in WBOC (Parsons 2006).

The data required for HAZUS-MH is assembled in Table 4 Profile Hazard for Case Study. HAZUS-MH also provides worksheets to help organize the data. The data comes from various sources. For example, in Table 5 having identified the event as a riverine flood, historical impact data is assembled from previous events.

Table 4 Profile Hazard for Case Study

HAZARD: Flood – Seaford-DE	
Summary of Risk Factors	
Rank of factors for local profile	Period of occurrence: June 25, 2006
Severity score: high	Probability of event:1% (100-year flood)
History: (similar events) 40	Warning time: 1 to 2 days very certain, 10 days trends.
Vulnerability: (Guessing) 75	Major contributor(s): Low elevation, East coast State, Major river
Maximum Threat: 80	Risk of injury? Yes, and risk of death
Probability: 80	Potential for facilities shutdown? Yes. Major roads for 30 days or more
Total score: 275	Percent of affected properties that may be destroyed or suffer major damage: guessing 10% of local road network
FLOOD (HAZARD) PROFILE (DATA)	
Background and Local Conditions	
Delaware has moderate risk for snowfall, has more than just a few but not frequent risk for thunderstorms, has moderate to low risk for wind, and some risk for hurricanes. The overall composite risk is moderate. Sussex County in Delaware is along with other U.S. counties with the greatest number of federal disaster declarations (USGS 2006). Seaford is located at 38°38′41″ N, 75°36′58″ W (38.644654, -75.616107), in southwestern Delaware. This area has low elevation, prone to flooding. Seaford's weather has a mild subtropical climate consisting of hot, humid summers and mild winters, moderated by the Atlantic Ocean. Common to have flooding event occurring also in the Maryland neighboring area, having to share solutions for traffic. Local transportation infrastructure usually in good and fair conditions, the traffic Level of Service is A to C. Area likely to be heavily impacted by climate change and global warming.	
Historic Frequency and Probability of Occurrence	
Flooding is the most common disaster type in the U.S. and for Sussex County. Considering similar events since the 1960's registered as a Federal Disaster Declaration, the number of events are 4. Earlier events lack easily accessible sources of information. Table 5 shows the events and their related damages. Figure 25 (Croope 2009) shows the related graph considering the time trend among Federal Disaster Declarations (Other different and minor events have taken place in other years).	
Severity	
Considering other areas in the U.S. areas, Delaware is considered a moderate risk area. However, Sussex County, Delaware is the area that most frequently experiences disasters, which matches (on a par with other areas that have received about the same number of Federal Disaster Declarations) (USGS). In this sense the risk for Flooding can be considered high. According to the flooded area map developed in ArcGIS and studies about global warming, events like the 100-year storm and other more rare events (i.e. 500-year storm) can increase in frequency and strength.	

Continue Table 4

Historic Losses and Impacts
Great damage has occurred to transportation infrastructure, crops, buildings, and some loss of lives (NOAA). The 2006 flood impacts list for Seaford area includes: • damage to the police department situated in the city of Seaford, and the Seaford School District parking lot, • barricades and high water signs emergency repairs and placement in the Town of Georgetown, totaling \$1,905, • traffic control and other security measures of the Delaware State Police, totaling \$9,822, • road and bridge repair under the responsibility of the Delaware Department of Transportation, totaling \$341,888, and • road repair work at the Delaware Technical and Community College, totaling \$13,340.
Designated Hazard Areas
The elevation profile map and the flooded area map developed earlier using ArcInfo show the areas most prone to flooding. They were built prior to the base map developed in HAZUS-MH. The use of HAZUS-MH software is to do a deeper analysis of the problem.

Source: Modified from HAZUS-MH (FEMA 2004).

Table 5 Worksheet for Hazard Identification and Characterization

A	B	Hazard	Hazard	Years	No. of Events	Impacts (2006 US\$)	Available Data Sources and Maps
√	√	Flood (Riverine)	Flood (Riverine)	1962 to 2006	4	#126 - \$21,391,487 #1017 - \$8,907,958 #1205 - \$3,721,100 #1654 - \$370,000 40 families temporarily homeless.	FEMA Disaster Research Results for Sussex County (2007). PERI Presidential Disaster Declarations (2007). WBOC News (Parsons 2006).

Source: modified from HAZUS-MH (FEMA 2004).

The results of the HAZUS-MH analysis include an estimate of the exposure of the transportation system (Table 6) and the amount of debris to be removed (Table 7).

Table 6 Estimate of Transportation System Exposure

Transportation System Dollar Exposure

October 27, 2008 — *All values are in thousands of dollars*

	Highway	Railway	Light Rail	Bus Facility	Ports	Ferries	Airport	Total
Delaware								
Sussex								
Segments	205,419.68	31,130.00	0.00	0.00	0.00	0.00	67,754.40	304,304.08
Bridges	14,754.85	0.00	0.00	0.00	0.00	0.00	0.00	14,754.85
Tunnels	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Facilities	0.00	0.00	0.00	1,188.10	0.00	0.00	5,940.50	7,128.60
Total	**220,174.53**	**31,130.00**	**0.00**	**1,188.10**	**0.00**	**0.00**	**73,694.90**	**326,187.53**
Total	**220,174.53**	**31,130.00**	**0.00**	**1,188.10**	**0.00**	**0.00**	**73,694.90**	**326,187.53**
Study Region Total	**220,174.53**	**31130.00**	**0.00**	**1,188.10**	**0.00**	**0.00**	**73,694.90**	**326,187.53**

Table 7 Estimated Debris to be Removed

Debris Summary Report

October 27, 2008 — *All values are in tons.*

	Finishes	Structures	Foundations	Total
Delaware				
Sussex	1,709	323	765	2,797
Total	**1,709**	**323**	**765**	**2,797**
Scenario Total	**1,709**	**323**	**765**	**2,797**

HAZUS-MH helps identify possible mitigation measures based on an analysis for each type of hazard, event scale and frequency, geographical features, existing infrastructure in the geographical area (the best analysis embedded in the software is for buildings), and time (different expected impacts day/night). The selection of mitigation options must follow FEMA's "STAPLEE criteria", which takes many factors into consideration to determine the feasibility of a mitigation strategy, specifically social, technical, administrative, political, legal, economic, and environment. These criteria show opportunities and constraints for mitigation measures as follows (Rock Island County 2008):

- **S**ocial criteria develops a community consensus for implementing the mitigation measures,
- **T**echnical criteria take care of technical feasibility, which includes effectiveness, secondary impacts, implementation and sustaining technical capabilities,
- **A**dministrative criteria look at organizations, staff, and funding sources,
- **P**olitical criteria include the support for mitigation measures from stakeholders, political organizations and institutions both inside and outside the community,
- **L**egal criteria look for the appropriate legal authority to implement each individual measure, codes, ordinances, and etc,
- **E**conomic criteria looks at cost-effectiveness and impact of measures on future development, which benefits are expected to exceed the costs,
- **E**nvironmental criteria look for benefiting the environment.

HAZUS-MH analyses outputs for the case study are used to define mitigation options for the different types of damage to the infrastructure as a result of the flooding hazard. The inclusion of the resilience factor is something HAZUS-MH software and principles do not clearly address. The specific analysis of impact on roads does not exist in HAZUS-MH. In other words, HAZUS-MH gives no value for direct economic loss analysis for transportation. A summary of the outputs of mitigation measures for this case study is shown in Table 8, modified from FEMA's guide (FEMA 2004). The Transportation Highway Inventory table (Table 6) was imported and adjusted in excel for modeling and simulation, because the inventory in HAZUS-MH is not in a proper format to be an input in STELLA. Each named column in EXCEL must match the elements in the model in STELLA.

All the analysis to enhance the resilience of the transportation road system as opposed to a regular rebuilding or repair of the infrastructure system segments according to its original design is all developed later using the STELLA software. The rebuilding or repair of infrastructure according to its original design is defined by the FEMA recovery policy (Speer *et al.* Unknown; FEMA 2009b; FEMA 2009a).

Table 8 Summary of Mitigation Measures Based on HAZUS-MH

Mitigation Activities	Output	Completed Items
Preliminary options	Regulatory measures: • reinforcement of construction codes (i.e., elevate degree of protection for rehabilitation, elevate-road design to flood level, engineering design improvement, site access points, roadway/pedestrian paths) • incentives for mitigation measures implementation, flow regulation • education measures (public awareness) • natural resource protection measure (preserve and restore natural systems) Rehabilitation measures (cost, importance, vulnerability?): • structural and non-structural modifications of road segments (i.e. increase structural resistance – impact load, retrofit roadways, enlarge road shoulders) • improve highways lights and signs • remove, relocate, and/or to elevate roads/road segments to meet new performance objectives Protective and control measures • floodwalls, levee, warning system (i.e., based on weather forecast) • protective vegetation belts • review and build connections	HAZUS-MH mitigation insights OK
Review of options	Regulatory measures: • reinforcement of construction codes (i.e., elevate degree of protection for rehabilitation, elevate-road design to flood level, engineering design improvement, site access points, roadway/pedestrian paths) Rehabilitation measures (cost, importance, vulnerability?): • structural and non-structural modifications of road segments (i.e. increase structural resistance – impact load, retrofit roadways, enlarge road shoulders), • improve highways lights and signs • remove, relocate, and/or to elevate roads/road segments to meet new performance objectives Protective and control measures • floodwalls, warning system (i.e., based on weather forecast) • review and build connections	STAPLEE OK
Final list of options	"Impossible with current HAZUS-MH functions, for exception for the adoption of warning system already included in current results." Although the listed mitigation options could all be analyzed for US13, these options are later carefully reviewed to reach an improved resilience of transportation system goal. HAZUS-MH does not discuss resilience.	To be further explored in STELLA
Verification of options	No conflicting measures to mitigate hazard impact.	OK

Source: modified from (FEMA 2004).

4.6.3 Scope of STELLA Implementation and Measures of Resilience

The implementation of the case study in STELLA is to demonstrate how the framework can be used. To simplify the demonstration of the model, a sample of data for the

Seaford area was used, specifically US Route 13. Seven segments on US Route 13 in the Seaford area were selected for analysis.

The data related to US Route 13 was obtained by comparing the highway inventory from HAZUS-MH, and the road data from DataMIL, clipping it to fit the study region in HAZUS-MH and then highlighting the HAZUS-MH segment links to identify their given identification code. This process used the Select Feature tool, because when opening the inventory table in ArcMap or HAZUS-MH interface, the available tables did not combine the information in the "attribute table" for the "name" US13 segments and their "cost" value. To highlight US Route13 in GIS for a qualitative network assessment, the creation of this new layer helped set up the boundary for the later analysis. The model in STELLA cannot handle this spatial visualization, connections, and analyses, therefore the results from these different systems must be integrated. The working paper "Working with HAZUS-MH" (Croope 2009) describes in more detail how the results were obtained.

The CIR-DSS focuses on measures of resilience and system performance. While there are many different measures that can be used, the demonstration of the application focused on some relatively simple measures that were available for the area under consideration and were easily understood. These measures were recorded for each segment before the event, during the event, immediately following the event, during recovery from the event, and after restoration. They are:

- Capacity measured in vehicles per hour per lane
- Number of lanes available.
- The pavement condition index (PCI) based on a visual rating of surface distress normalized to a scale of 0 to 1.

Table 9 shows the seven segments used for analysis and the measures of performance or resilience prior to the event.

Table 9 HAZUS-MH US13 Simplified Inventory for the Study Region

OBJECTID	ID	Name	Length	Traffic	Cost	NumLanes	Pavement	Capacity
4	DE000060	Sussex Hwy	10.83	0	$32,206.20	4	0.7	7600
5	DE000066	Sussex Hwy	0.88	0	$2,628.59	4	0.7	7600
6	DE000068	Sussex Hwy	2.54	0	$7,543.82	4	0.7	7600
7	DE000069	Sussex Hwy	0.33	0	$987.21	4	0.7	7600
8	DE000085	United States Highway	3.62	0	$21,534.23	4	0.7	7600
21	DE000509	United States Highway	0.77	0	$4,555.43	4	0.7	7600
22	DE000511	United States Highway	0.27	0	$1,623.54	4	0.7	7600

Source: modified from HAZUS-MH MR3 (FEMA 2007e).

CHAPTER 5 BUILDING A MODEL IN STELLA FOR CIR-DSS

5.1 Introduction

Following the steps for developing a model in STELLA as shown in Figure 9, and the CIR-DSS framework as shown in Figure 2, this chapter describes how the CIR-DSS model is built in STELLA and then tested. Details of the development process, sources of data, and the model are provided in the working paper "Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Building the Model in STELLA" (Croope 2010c).

This model development process recognizes that improving the resilience of the critical infrastructure system is a process of continuous improvement as shown in Figure 25. The spiral mechanism represents the learning and evolving system beginning with the occurrence of a disaster. As knowledge increases over time and the decision making process evolves, the critical infrastructure systems are better managed considering past events, other relevant variables, and stakeholders involved in the process.

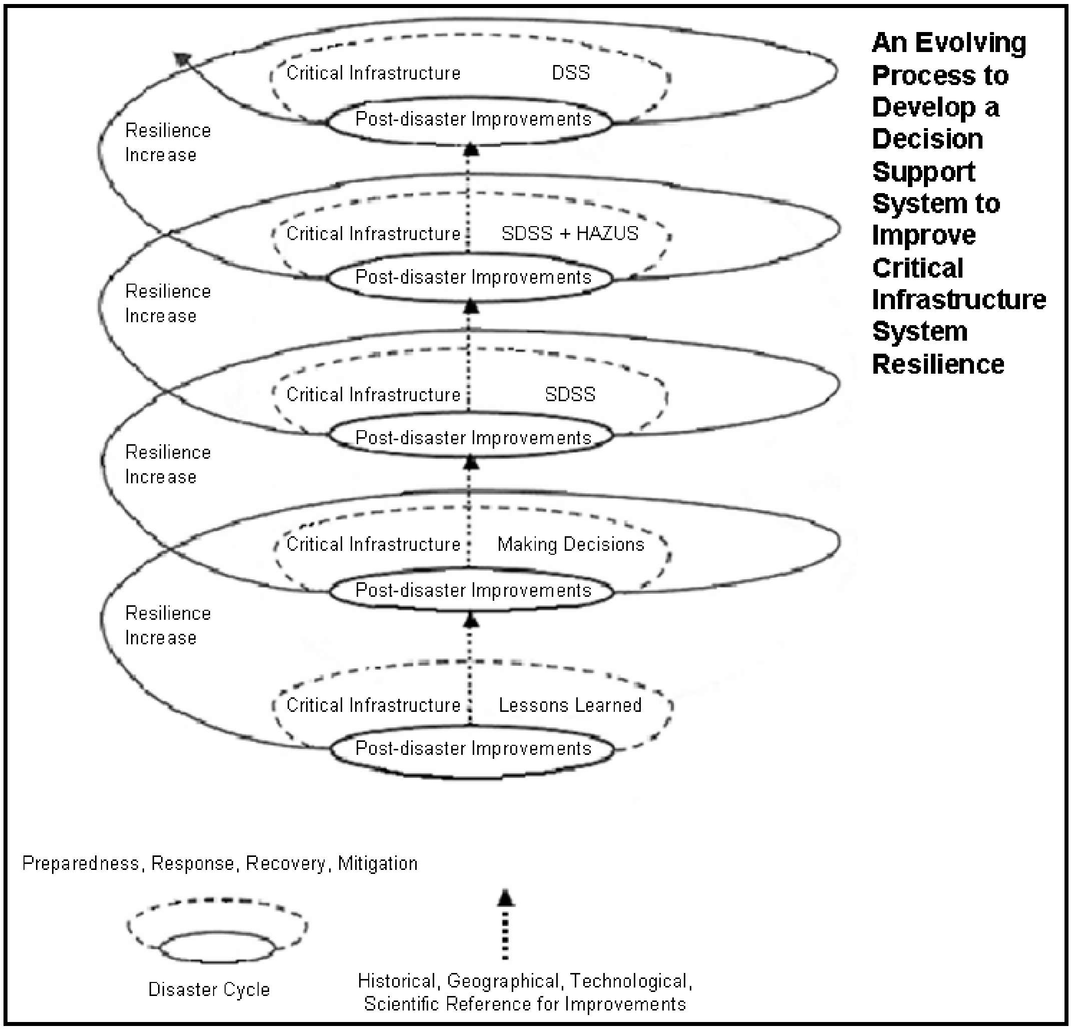


Figure 25 Critical Infrastructure Resilience DSS Improvement Diagram
Source: Modified from MIT (Unknown).

A better description of each of the elements involved in building the model in parallel to the learning process in STELLA (Figure 9) is shown in Table 10. The table shows the steps in the model development and the parallel step in the learning process.

Table 10 CIR-DSS Elements in STELLA Model-Construction and Learning Processes

Define the Issue			
The model is intended to help supporting decisions to improve resilience of critical infrastructure systems in a post-disaster context, by: • Mitigating CIS failure, disruption, and damage; • Promoting better physical conditions for systems to work; • Ensuring continuity of flow of people and goods.			
	Model-construction Process	***Learning Process***	
Develop the Hypothesis	The resilience of the network can be improved by investments in infrastructure	Government, stakeholders, researchers, students	***Identify the Target Audience***
Test the Hypothesis	The hypothesis is built by constructing the model including the components of the "System Dynamic Diagram of Decision Support System for Critical Infrastructure System Resilience". The model developed used a mix of different possible infrastructures including Main Chain and Attribute Tracking.	Demonstrate the use of a new approach for helping to make decisions when dealing with the challenges of critical infrastructure systems that needs to work even when challenged by disasters. Build a model as a CIR-DSS to assess, forecast, communicate risk and failure, generate solutions, evaluate impacts, make decision, and implement solutions.	***Define the Objectives***
Draw Conclusions	The model is large, complex; allow to identify problems and to fix them without having to rebuild the whole model. It also allows minor changes for using converters instead of flows and stocks as needed. It enables to link different entities that do not share the same units, reflecting real-world dynamics. The model showed and validated the framework represented by the diagram for the Critical Infrastructure Decision Support System. The model can be customized to work with more details and produce aggregated results, transitioning well between the project/operational level and the management/strategic level. The model can continue to grow and include more variables and more interdependency among variables.	Active learning strategy – includes constructing the model and simulating different options for making decisions to improve the resilience of CIS. It allows understanding the need for some specific variables to produce determined results and to modify calculations to adjust to changes through time to reflect infrastructure behavior. It allows verifying feasibility of each step of the model as it is being built. It also requires a continuous learning process not only to enable a good structure to the model, but also to deal with the software tools and interface. It allows working with basic mathematical functions to more elaborate equations. It allows getting insight of things that can be better built. It also allows seeing where the software system platform is limited showing the system behavior in the interface, where graph and tools limits the way the model can be presented and understood to the audience.	***Define the Learning Strategy***
Assess Robustness of Conclusions	A sensitivity analysis is included in the model. It shows the output of the model working with the current values associated for simulation, and also tests the model assigning random numbers. It proves the model works better for greater frequencies of storms for the case of Delaware and the current parameters included in the model. This shows the model is fairly capturing the real-world problem being investigated.	Through the use of model for simulations, and presentation of the process and results. Includes the key elements for including in the communication part of a Decision Support System. Through the interface enable the audience to capture the main idea of the model, including the possibility for seeing how/what is the model behind the simulation presented. Allows and motivate people to "ask more questions and investigate other possibilities".	***Implement the Learning Strategy***

Source: modified based on isee systems (2004).

As described in Section 1.3.4, there many steps involved in the CIR-DSS model development. Recognizing that the CIR-DSS framework has several subsystems, the step-by-step process (described in Section 3.2) when integrated with the steps to develop a model in STELLA (Figure 9 and Table 10) provides a way to show the dynamics inherent in modeling the resilience of critical infrastructure systems in a post-disaster atmosphere. The model is also broken into parts to fit each interaction among the subsystems components. The relationship between the model development steps and STELLA is shown in Figure 26.

The model framework recognizes eight steps:

Step 1 – getting local infrastructure information, initializing the system

Step 2 – getting system performance measures

Steps 3 and 4 – degrading system performance because of a disaster

Steps 5 to 7 – improving system performance

Step 8 – assessing performance.

Figure 25 shows the CIR-DSS model framework developed in STELLA.

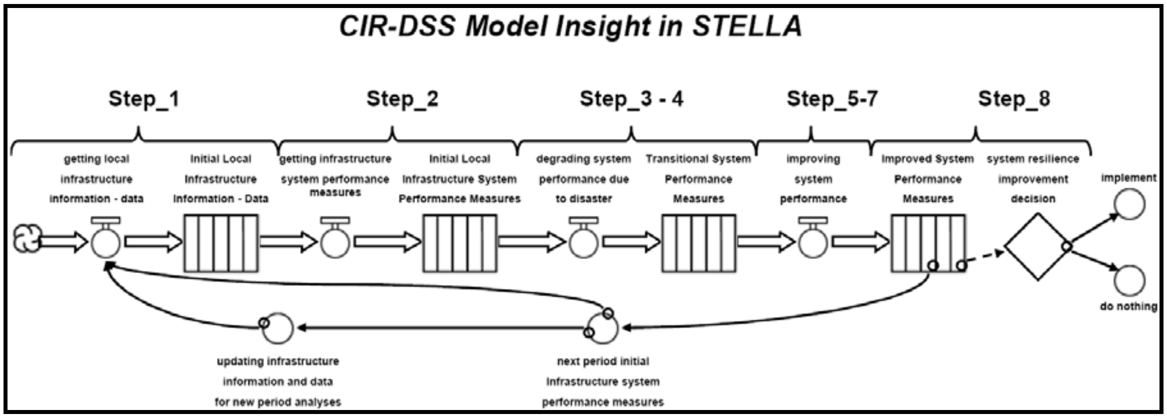


Figure 26 CIR-DSS Model Framework
Source: Croope (2010c).

These eight steps shown in Figure 25 were deliberately designed to view the changes in infrastructure condition and performance throughout the disaster event (before event normal conditions), during event, immediately after hazard onset, after event, and future. The future infrastructure condition and performance consist of long-term damaged infrastructure fix alternatives and improvement for recovery and mitigation for the case study infrastructure system network.

5.2 <u>Background</u>

Preliminary graphs to illustrate a reference behavior pattern (RBP) with relative measures (normalizing values) of such infrastructure are shown in Figure 26 and Figure 27 for two scenarios: “as is”, and “to be” respectively.

<u>As is</u> RBP considers the normal process of the transportation network system performance over time, with floods as the type of disaster, and the transportation system back in operation and repaired or reconstructed to the original design. The time span relates to the occurrence (impact) of a disaster, which relates to the time where the infrastructure is no longer

in service due to disruption or failure. This time during which the infrastructure is unavailable can vary according to the level of damage or destruction and the required repair or rebuilding. The degradation of service in the transportation network, in this case, is a secondary factor, not included in the model at this point (e.g., partial road closure such as only 1 of 2 lanes in operation). The assumption is that without infrastructure improvements and mitigation measures adopted (in relation to the improvement of the resilience of the system) a similar behavior pattern will be exhibited when a similar disaster occurs. As a rough approximation, the performance of RBD for the system, shown in Figure 27, degrades/collapses with the occurrence of a major disaster, is then fixed and the cycle re-starts at the level planned according to the original design. The curve goes down after some oscillations, drops to no functionality and after some time, rises and gives place to another phase of drops after some oscillations.

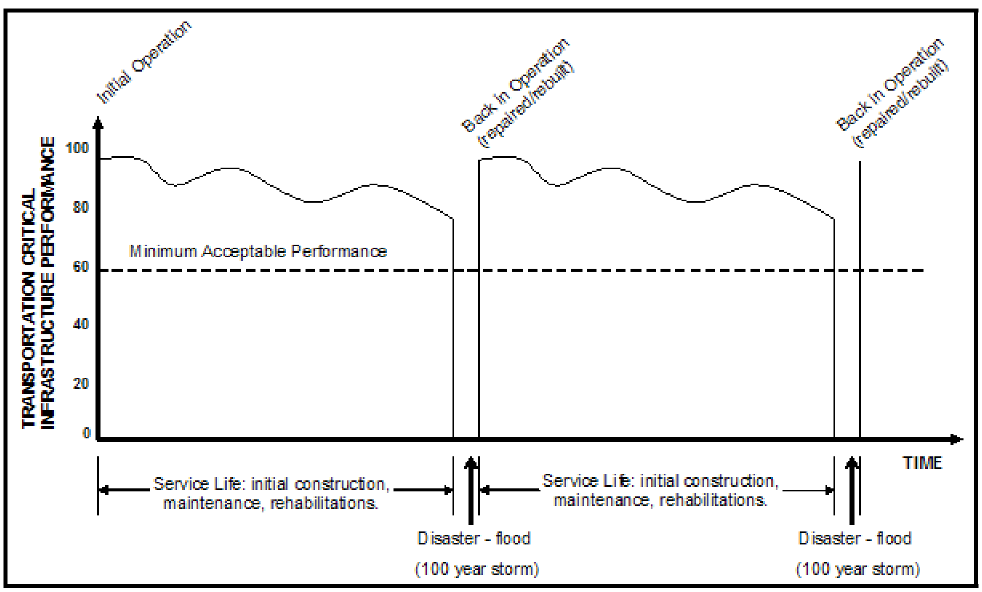


Figure 27 Reference Behavior Pattern for System "As Is"
Source: based on USDOT and FHWA 2002.

<u>To be</u> RBP considers an improvement of system resilience after disaster(s), an overall recovery and mitigation action combined. This means the system could be improved by (any or all of these items):

- reinforcing structures (rebuilding),
- changing the network (e.g. location of roads, bridges),
- adding segments to the network (new construction projects),
- replacing structures with other more resistant features,
- reinforcing building codes for new construction, and
- any other possibility that adds to reaching a mitigation strategy.

One can expect to see the system better withstand bigger loads or stresses, decreasing vulnerability, and degrading less due to the impact of disaster. Hypothetically, the improvement of the system will reach the level of no absolute/complete disruption or failure, meaning no major damage or destruction impacts the infrastructure. Of course, in real life, man cannot expect to make structures in a "built forever" condition, becoming a permanent service through time, because disasters can vary in type, intensity, and periods of occurrence. Degradation of the transportation network service assumes a more relevant role in this type of scenario. Learning capabilities, technology evolution, a stakeholder's will, and commitment can impact the overall outcome of the infrastructure system resilience.

The To Be RBP considers the most recent FEMA federal disaster declarations (in terms of years) of flooding for Sussex County, in Delaware where Seaford is located (FEMA 2007a). It helps addressing the events interval periods, a better approach to reality. The improvement of the resilience of a system, for this approach, is independent of past actions.

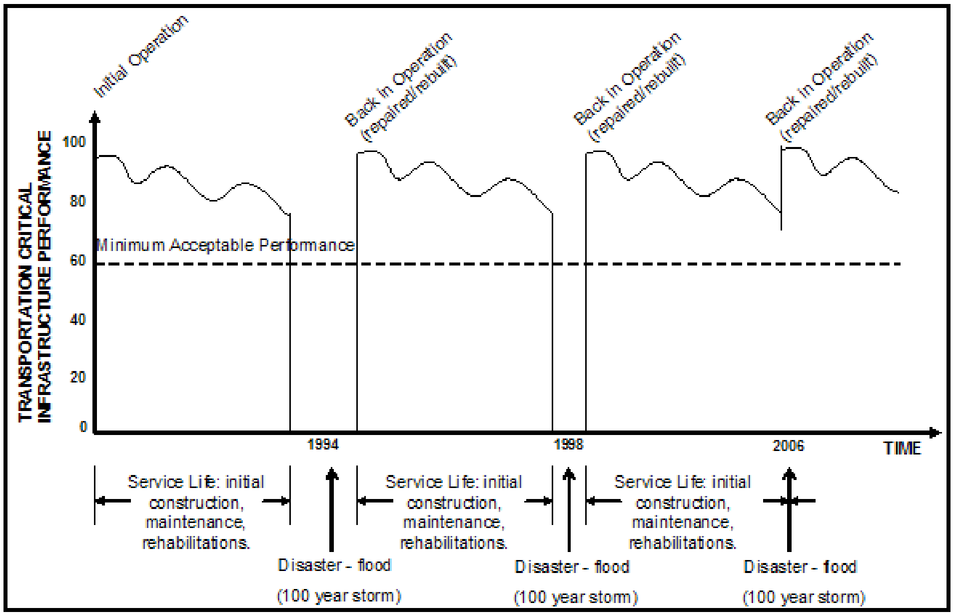


Figure 28 Reference Behavior Pattern for System "To Be"
Source: Based on USDOT and FHWA (2002).

The To Be RBP shown in Figure 28, works a little differently than the As Is RBP. The time span between the occurrence of a major disaster disrupting the infrastructure serviceability, and the system returning to its normal operations, decreases over time. However, the performance of the system, even though improved, does not go above 100%. This is because the repair, rebuilding or even replacing (segments) of the infrastructure, address the events in anticipation of final disruption and damage. The comparison of the system before and after the disaster serves as a basis for the improvements that the system needs to decrease its vulnerability, and consequently lessen damage and destruction, which will lead to failure. A literal comparison of the system performance pre and post event in terms of percentages, and the structural quality of the infrastructure requires a different graph, and thus is not the purpose or priority of this model. To lessen the impacts of disasters however is the purpose behind making a system resilient. This can be seen as making the infrastructure system performance more stable and continuous over time.

5.3 Key Measures of Resilience

To track the resilience of the infrastructure network, each segment of the infrastructure represented is individually modeled in terms of relevant variables as a means to define and show the segment attributes. These infrastructure segments, attribute variables are:

- Number of lanes
- Pavement condition index (PCI)
- Capacity (in vehicles per hour)
- Level-of-service (related percentage flow of traffic)

Another variable that is added to show the resilience of the infrastructure system is “disruption” for the timeframe during disaster. Post-disaster damage (as considered in the case study) was not able to immediately return to normal operation. The overall time of disruption is considered later when looking at alternatives to fix damage of the infrastructure.

Using the network resilience definition in Section 1.3.1, the road network and flooded area developed in the GIS system, and the road inventory from HAZUS-MH later modified in EXCEL, changes in performance are tracked over time.

5.4 Step 1 - Getting Local Infrastructure Information.

The first step includes choosing a critical infrastructure system, a study area and a hazard. The critical infrastructure system chosen is transportation including roads and bridges. The study area is Seaford in southern Delaware (U.S.A.), focusing the analysis on a limited geographic area. The hazard is flooding at the scale of a federal disaster (in particular the one that happened in June 2006).

This step defines the hazard type (in this case the flood as represented by the rain map in Figure 16), the study area (US Route 13 in Seaford, Delaware), the transportation infrastructure of interest, the value of that infrastructure, and the role of the decision-maker. The data and information for this step was assembled using GIS and presented in Chapter 4.

The relevant part of the CIR-DSS framework is shown in Figure 29.

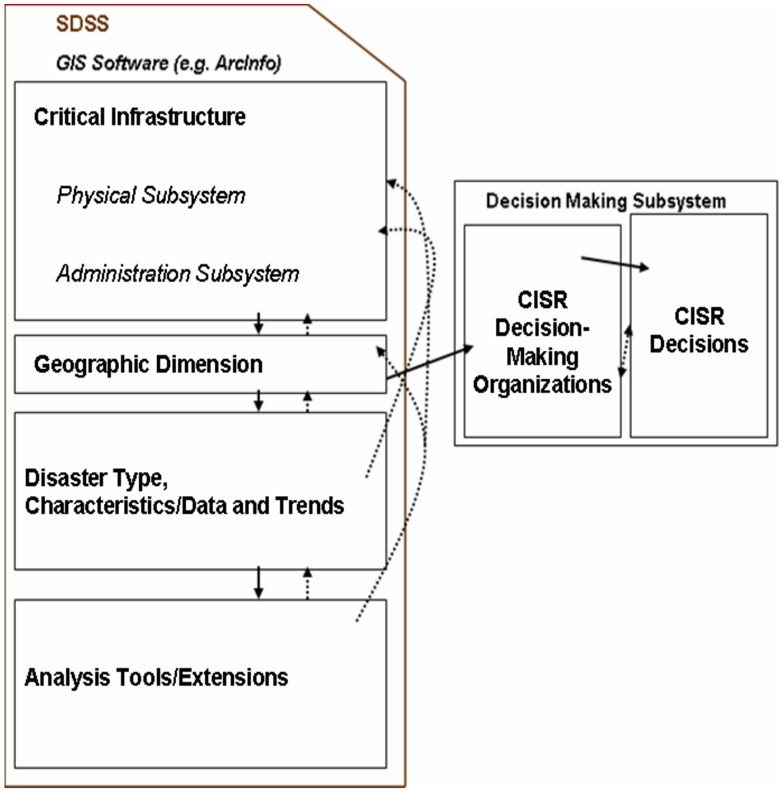


Figure 29 Step 1 - CIR-DSS Framework

5.5 Step 2 - Getting System Performance Measures

Step 2 involves a diagnosis of the problem based on the infrastructure condition before the event and the potential hazard. This step also includes doing a vulnerability assessment, an impact assessment, a damage assessment, and developing initial insights into strategies for recovery and mitigation. Step 2 starts with developing the model to get the infrastructure system performance measures for the infrastructure system in normal condition – before the disaster.

This involves:

- Define and include data generated by other software (e.g. GIS and HAZUS-MH), including
    - Cost

- Vulnerability assessment
- Impact assessment
- Damage assessment

- View the phases in the model and the changes in performance
  - Pre-disaster - “before event condition and performance measures”,
  - During the disaster -“during the event infrastructure behavior”,
  - Post-disaster - “immediately after disaster condition and performance measures”
  - Recovery - “post disaster strategies for recovery or mitigation, and condition and performance measures.”
- Compute variables, for example:

$$V = f x \ (I - AC)$$

V= Vulnerability (in \$), I = Impacts (in \$) and AC = Adaptive Capacity (in \$)

Compute condition and performance metrics in the first phase (Pre-disaster).

Figure 30 illustrates how STELLA views the relationships among the variables.

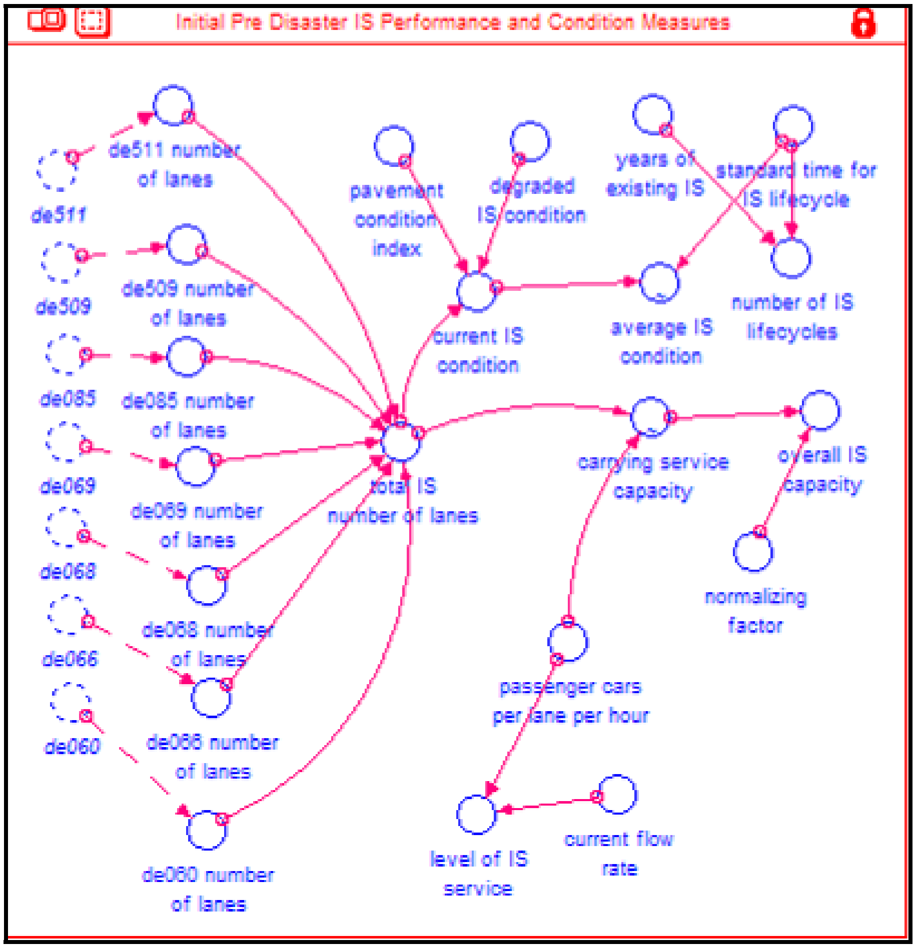


Figure 30 Initial Pre Disaster IS Performance and Condition Measures Framework

At this stage the model

- Shows:
    - Infrastructure vulnerability and exposure evaluation
    - Impacted infrastructure in case-study area
    - Case study area re-dimensioning, inclusion of “warning system” mitigation strategy, and river impact on infrastructure
- Includes:
    - current (pre-disaster) physical condition (absolute and percentage),
    - current carrying service capacity (absolute and percentage), and

- current level of service (absolute and with the current flow rate percentage value which translate the given qualitative measure “B”).

The relevant part of the CIR-DSS framework is shown in Figure 31.

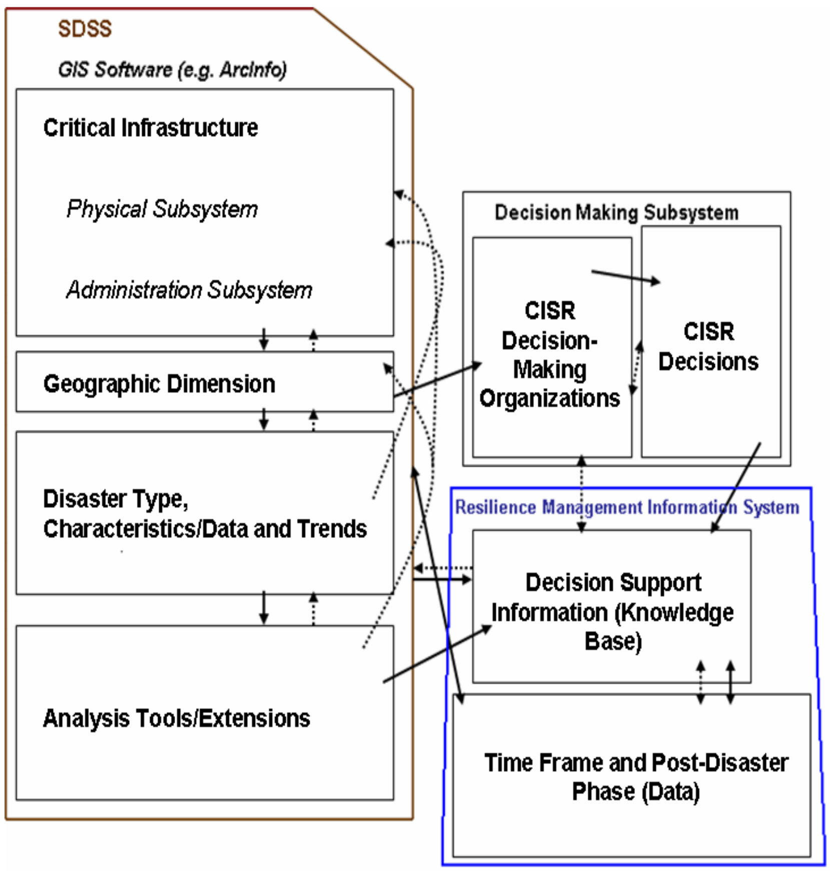


Figure 31 Step 2 - CIR-DSS Framework

5.6 Step 3 - Compare pre and post-event functional system

Steps 3 and 4 focus on the second phase of the changes in condition and performance. This second phase establishes the transition of condition/performance from the pre-disaster status to the status during the disaster. This includes a damage assessment of the impacted system segments identifying problems exclusively associated with the infrastructure.

Step 3 compares the pre and post-event functional system including CIS physical and administrative subsystem condition parameters. At this stage in the model’s development the constant three measures used to assess the system resilience for pre-disaster and post-disaster condition and performance available are:

- physical condition (absolute and percentage),
- carrying service capacity (absolute and percentage), and
- level of service (absolute and current flow rate as a percentage value of the flow for the qualitative LOS "B").

The measure for disruption is included in the calculation for system resilience for the "during-disaster" timeframe, as this measure address both the scale and intensity of the event, and how adaptable the system is to this challenge for normal operation. This is a temporary and transitional measure for showing the system's behavior at that particular moment.

Using the details of post disaster conditions, definitions of disruptions, estimated time to restore infrastructure services, funding sources, and pre-disaster conditions, values are computed for the flow rate of LOS, short term carrying capacity and pavement conditions for each phase or snapshot in time (pre-disaster, during the disaster, post-disaster). The computations are summarized in Table 11.

Table 11 Variables Computed in Step 3

Phase	**Pre-disaster**	**During the Disaster**	**Post-disaster**
Condition	✓	✓	✓
Carrying Capacity	✓	✓	✓
Level of Service	✓	✓	✓
Flow	✓	✓	✓
Disruption		✓	
Back in Service			✓
Resilience	✓	✓	✓

The current status of the system is shown in Figure 32.

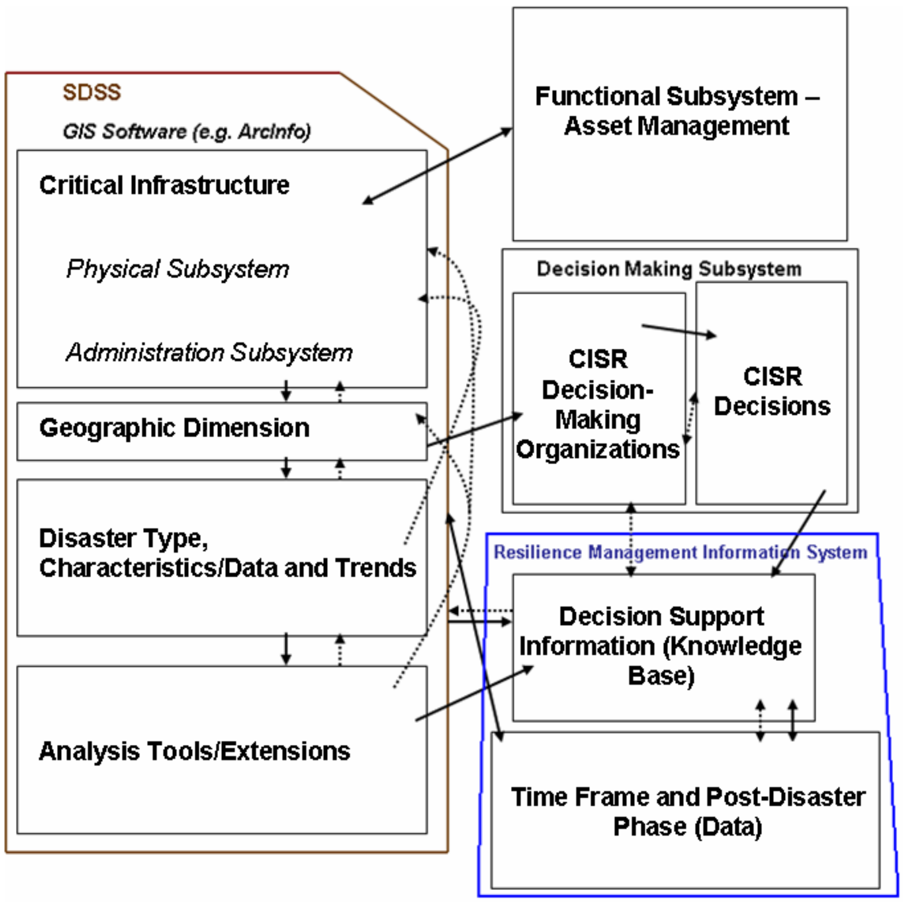


Figure 32 Step 3 - CIR-DSS Framework

5.7 Step 4 - Financial Implications

Step 4 uses the financial subsystem to identify needed resources to support normal operations. This step uses the costs computed in Step 1.

This includes:

- Cost and benefit-cost analysis for an alternative fix based on infrastructure improvement
- Cost of normal operations
- Stakeholders share of the financial responsibility over cost of normal operation

The current status of the system is shown in Figure 33.

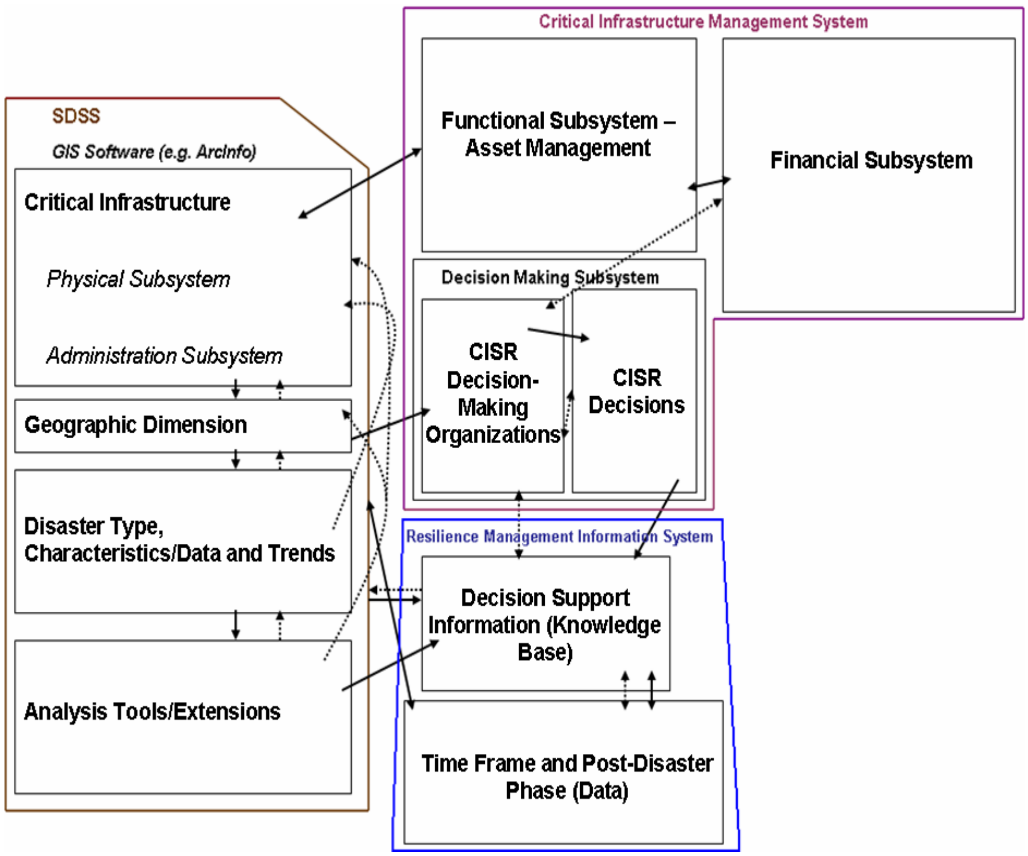


Figure 33 Step 4 - CIR-DSS Framework

5.8 <u>Step 5 - Impact Analysis</u>

This step considers disaster impacts, and identifies and forecasts resources required to recover and mitigate a damaged critical infrastructure (at specific sites). This includes:

- Estimation of resources required to fix the damaged infrastructure
- New financial share among stakeholders for fixing the damaged infrastructure
- Small performance and condition measures improvement if using the recovery approach
- Repaired damaged road segments back in service: “recovering usability”
- Recovery assessment resilience metrics

- FEMA's Mitigation Grant parameters and what is being used in the model
- Cost estimation of mitigation projects including resilience improvement and financial share among stakeholders
- Mitigation strategies and costs
- Infrastructure's initial and recovered condition comparison in terms of decreased vulnerability
- Mitigation projects' condition and performance in decreasing infrastructure vulnerability
- Resilience metrics calculation for mitigation

The current status of the system is shown in Figure 34.

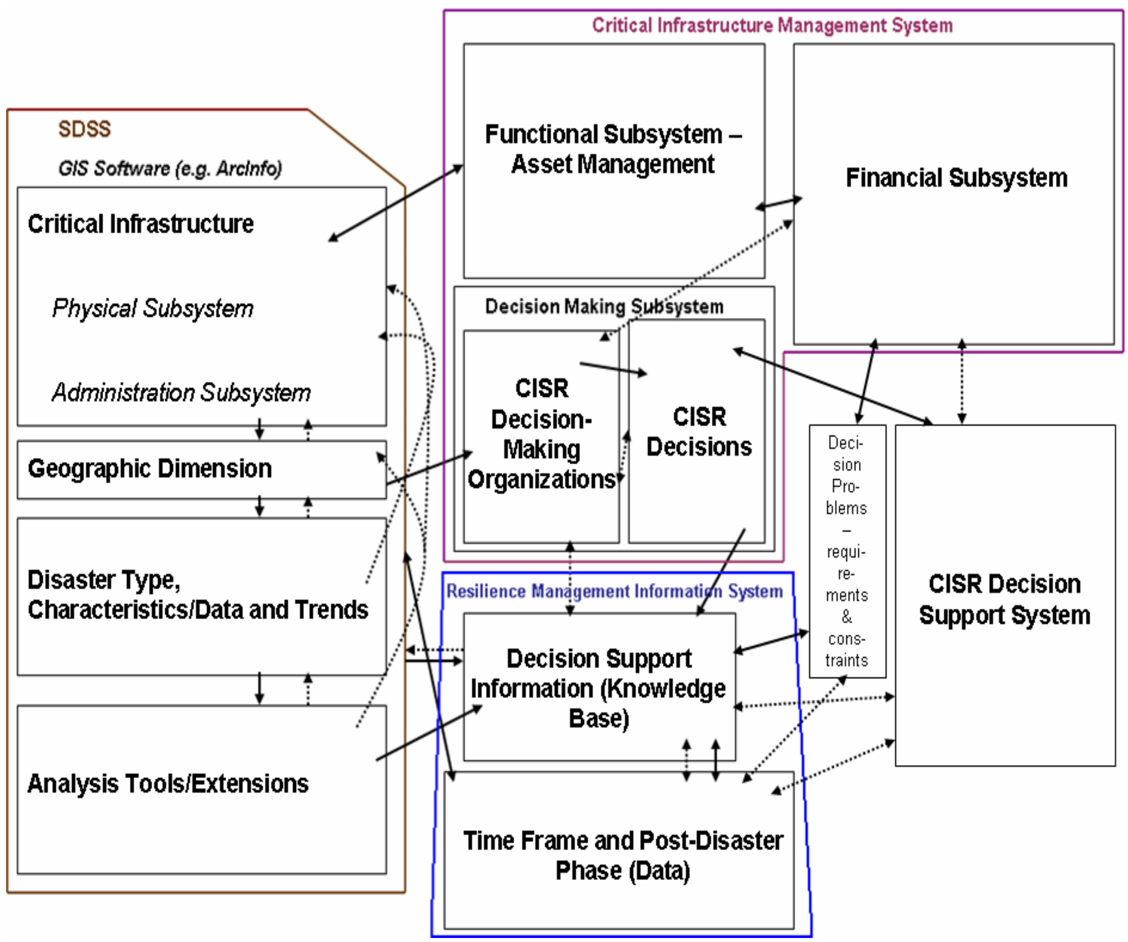


Figure 34 Step 5 - CIR-DSS Framework

5.9 Step 6 - Inclusion of Decision Makers

This step involves the consideration of how to recognize all decision-makers, and decision factors. It defines the scope of work and projects to restore CIS and enhance resiliency. Some of the decision-makers involved in the process were already included in Steps 1 through 3.

Specific actions include:

- Comparison of initial infrastructure vulnerability between recovery and mitigation projects
- Recovery and mitigation difference based on initial vulnerability values
- Computation of vulnerability, damage, historical impacts and future risk relationships for infrastructure
- Computation of disaster impacts as an input to benefit-cost analysis calculations
- Identification of categories of infrastructure benefits
- Calculation and presentation of direct economic impacts of road closures including travel time and travel delay time, for before and after-disaster
- Analysis of benefits and costs for recovery and mitigation projects including net present value (NPV)

The values are computed in Excel and presented as

- A recovery NPV graph
- Mitigation vs. recovery project investment result's "picture"
- Mitigation and recovery projects benefits summary and comparison

The current status of the system is shown in Figure 35.

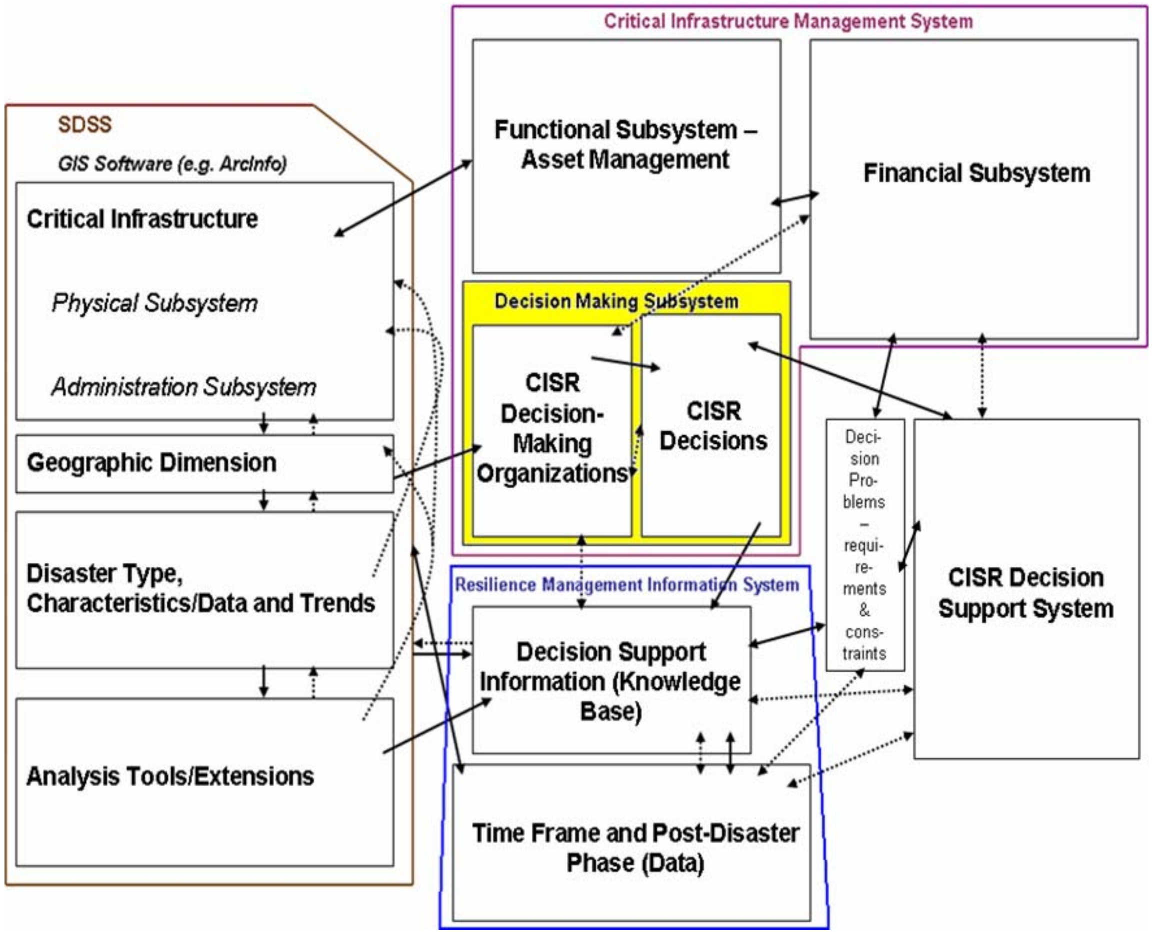


Figure 35 Step 6 - CIR-DSS Framework

5.10 Step 7 - Review Problem, Constraints and Requirements

This step involves reviewing the complex-system problem, constraints, and requirements including opportunities to improve system resilience. Specifically, this includes:

- Complete revision and adjustment of data and analysis to get meaningful results
- Inclusion of a scenario simulating stakeholders' request's for inclusion of cost adjustment for a mitigation project

Section (5.12) reviews the results and testing of the model in more detail. The current status of the system is shown in Figure 36.

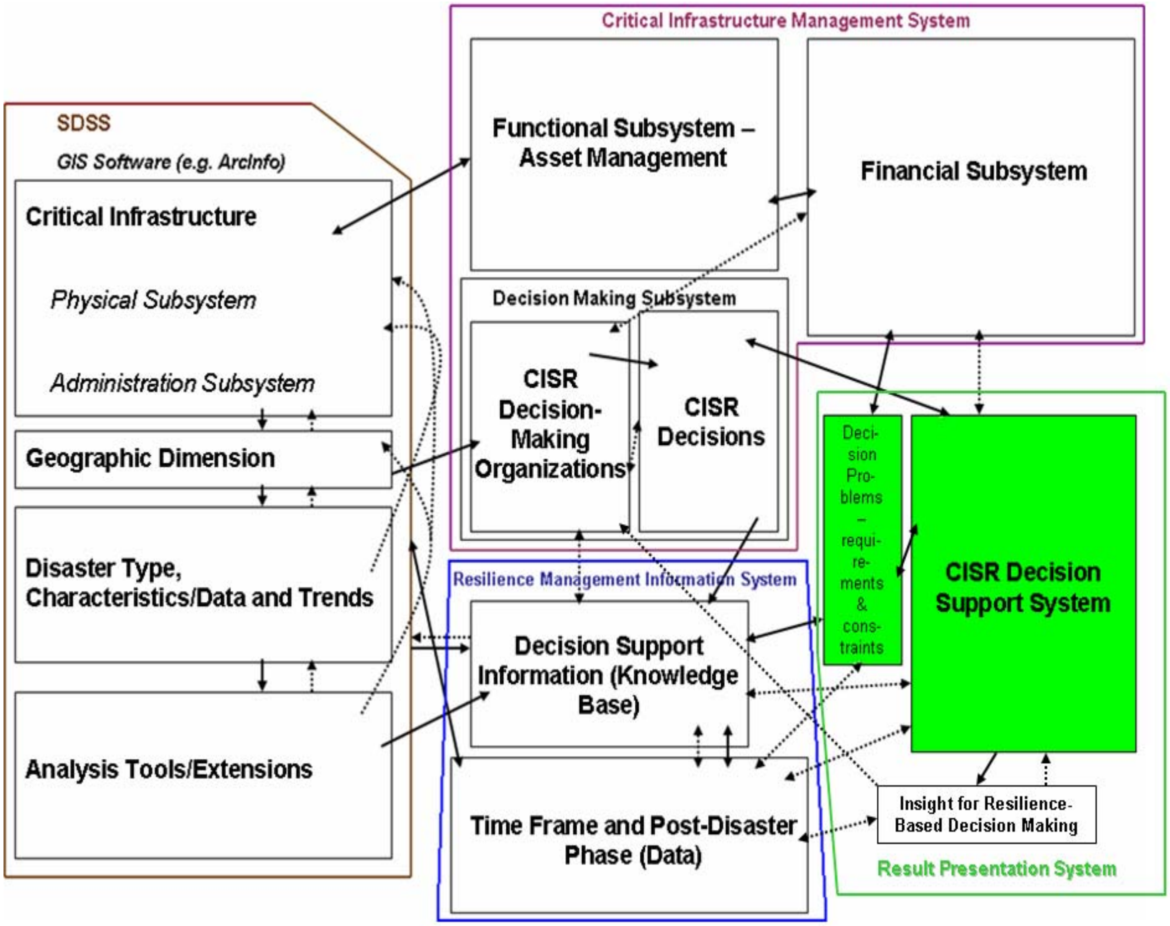


Figure 36 Step 7 - CIR-DSS Framework

5.11 Step 8 - Evaluation and Communication of Results

Step 8 is the evaluation and communication of results including presentation of the framework. 5.7 describes, in more detail, the process for building the interface. This step includes:

- Project NPV values for different probability events of (1%, 4%, and 8%) and benefits of both mitigation and recovery
- Recovery projects cost comparison with mitigation projects for the different 1%, 4%, and 8% probability of events

- Improvement of resilience calculation uses mitigation of another similar disaster occurrence. It considers the percentage of the infrastructure mitigated in relation to the overall case study infrastructure extension
- Infrastructure mitigated vs. overall infrastructure summary
- Improvement of resilience of system through time (slow): calculation and graph
- Change of resilience of infrastructure system capturing system dynamics through an event graph
- Comparison of project NPV results with and without sensitivity analysis - graphs

The current status of the system is shown in Figure 37. This is the complete framework as originally presented in Figure 2.

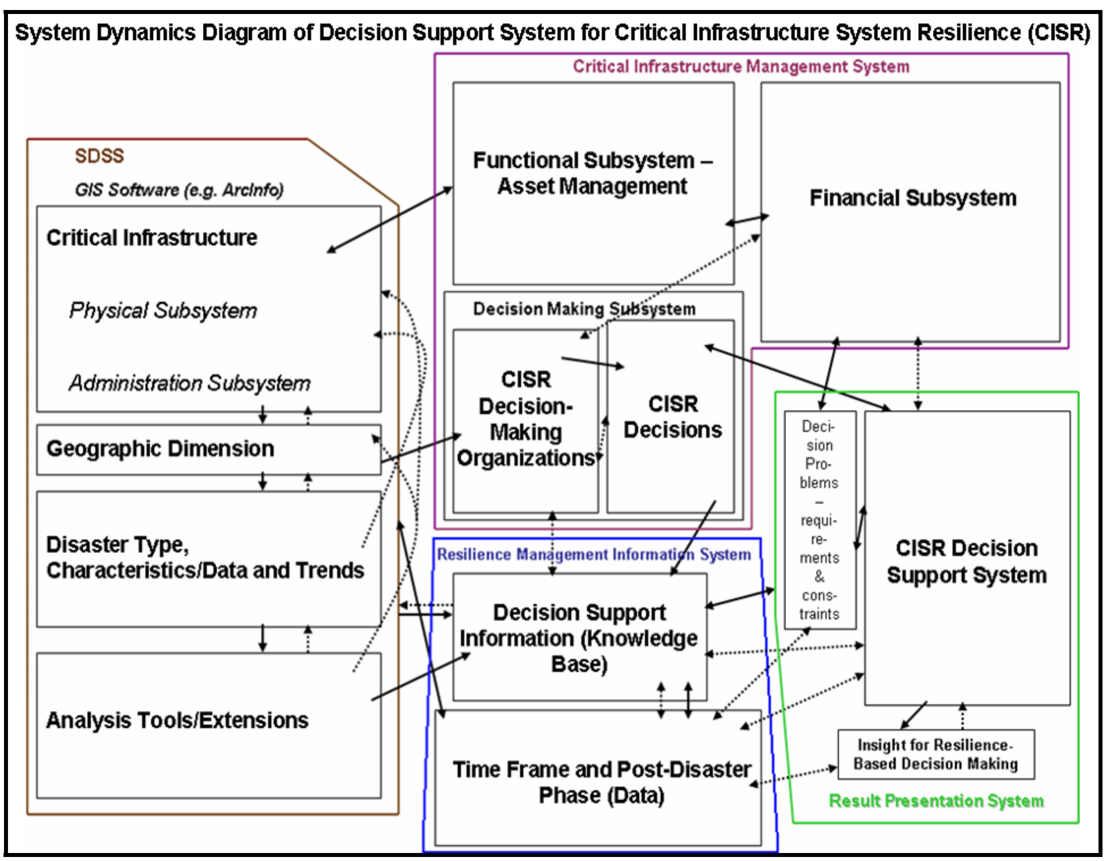


Figure 37 Step 8 – CIR-DSS Framework

5.12 Testing the Model

To explore how the model reacts to changes in input variables and parameters, a sensitivity analysis was undertaken. STELLA provides some functionality to assist with this process. The sensitivity analysis included in STELLA is for a one-time analysis only. This means that if the sensitivity analysis is conducted using different variables than those originally chosen, the current analysis will change. The working paper "Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Testing the Model" describes the process in detail including the use of STELLA (Croope 2010d).

5.12.1 Parameters Used in the Sensitivity Analysis

STELLA uses a number of parameters to control and define the scope of the sensitivity analysis. These include:

- Variables – in this case the value of damaged infrastructure segments; (damaged IS).
- Number of runs – in this case, 3, the default value.
- Variation type - "Incremental"
- Range of values – use a minimum value of $50,000 and a maximum value of $500,000

5.12.2 Model Outputs

The user can also define the form of the output (a bar graph, or a scatter plot) depending on the number of variables of interest. In this case, a bar graph was chosen with the following variables:

- Net present value of the cost of recovery assuming a 1% probability of a 100 year storm event in the case study area (recovery NPV 2),

- Net present value of the cost of recovery assuming a 4% probability of a 100 year storm event in the case study area (recovery NPV),
- Net present value of the cost of recovery assuming an 8% probability of a 100 year storm event in the case study area (recovery NPV 3),
- Net present value of the cost of mitigation and recovery assuming a 1% probability of a 100 year storm event in the case study area (mitigation NPV 2), and
- Net present value of the cost of mitigation and recovery assuming a 4% probability of a 100 year storm event in the case study area (mitigation NPV)

5.13 Summary

This chapter summarized the steps involved in developing the model in STELLA to demonstrate the application of the CIR-DSS framework. Throughout the model development pavement condition, carrying service capacity (lane availability), level of service, and disruption were used to track performance and resiliency. Alternative scenarios, particularly recovery versus recovery and mitigation can also be evaluated using a cost benefit analysis. Further documentation is available in the working papers "Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Building the Model in STELLA" (Croope 2010a) and "Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Testing the Model" describes the process in detail including the use of STELLA (Croope 2010d).

The following chapter (Chapter 6) describes the development of the model's interface. Chapter 7 then presents the model results and evaluates the results.

CHAPTER 6 BUILDING THE INTERFACE

This chapter describes the development of the interface for the model developed in STELLA. Details of the development process are included in the working paper "Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Building the Model's Interface in STELLA" (Croope 2010a).

6.1 Overview

The interface complements the model analysis by generating the results in a form that is useful to stakeholders in terms of costs, benefits, trade-offs between investments, evaluating alternative projects and approaches looking at improvements in effectiveness and system resilience. This is part of Step 8 in the model development and is represented by the "presentation of results of analyses" in the lower right part of the CIR-DSS Framework shown in Figure 2.

6.2 An Example – Annotations for Step 6.

To illustrate how the annotations work in the model, Step 6 – the inclusion of decision makers is shown in a step by step way. The annotations are as follows:

- Defining vulnerability using an information button (Figure 38).
- Information on historical data on damage (Figure 39).
- Information on the damage and benefits components (Figure 40).
- Information on the data for the cost-benefit analysis (Figure 41).
- Information on the net present value calculation (Figure 42).
- Summary results (Figure 43).

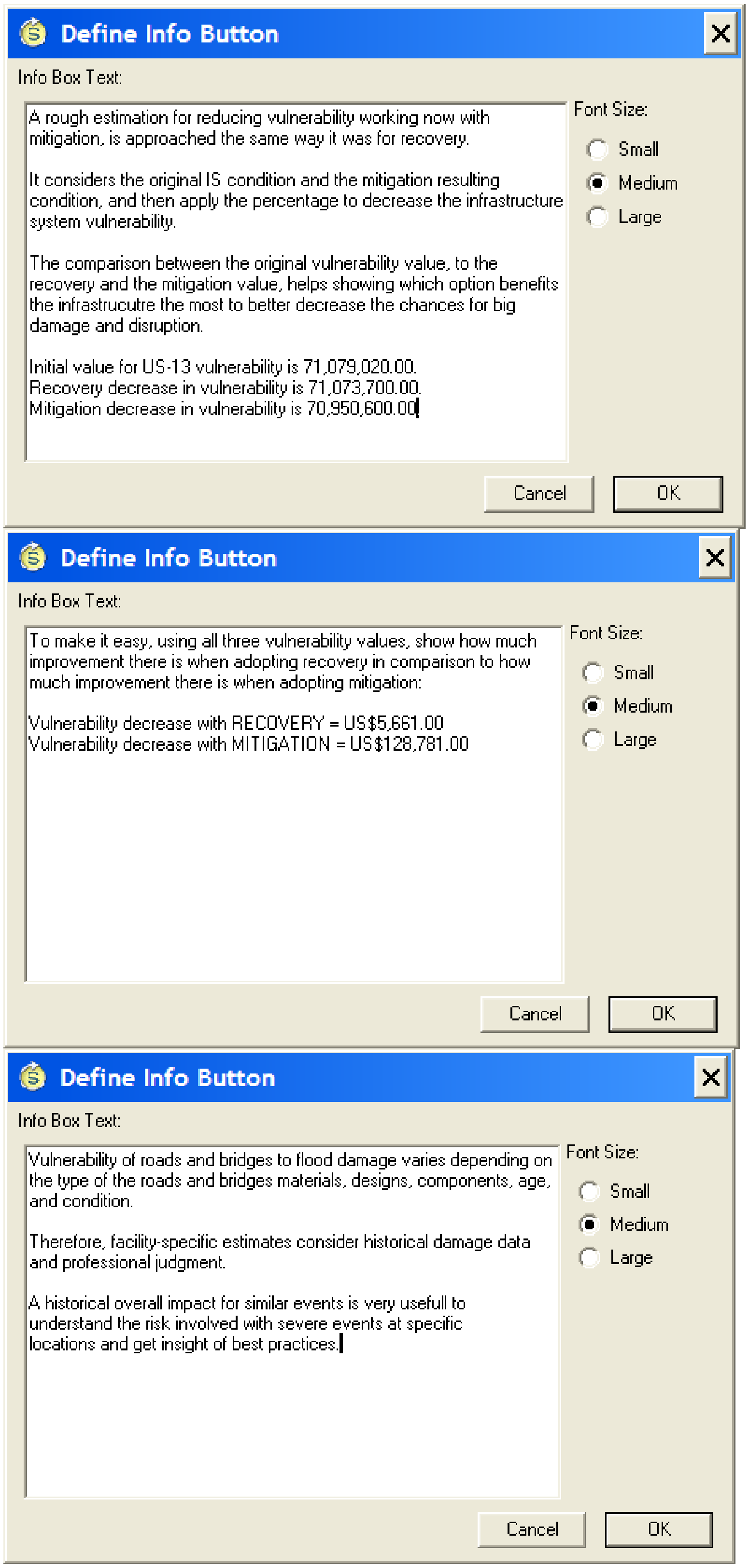
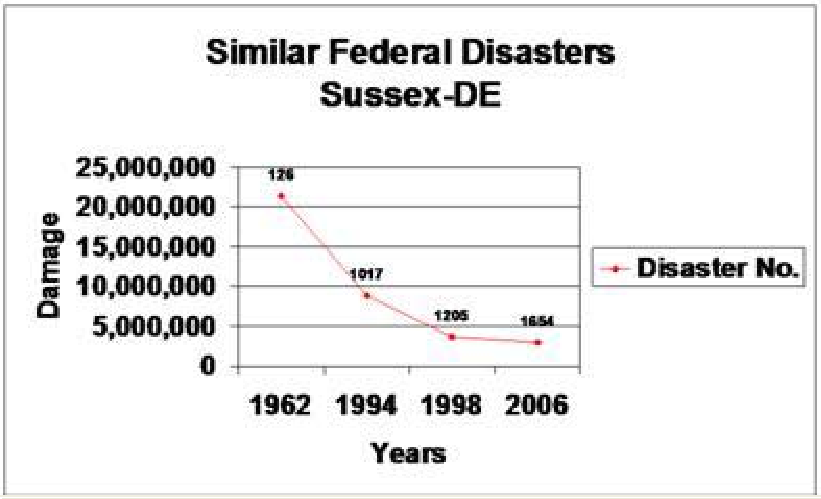
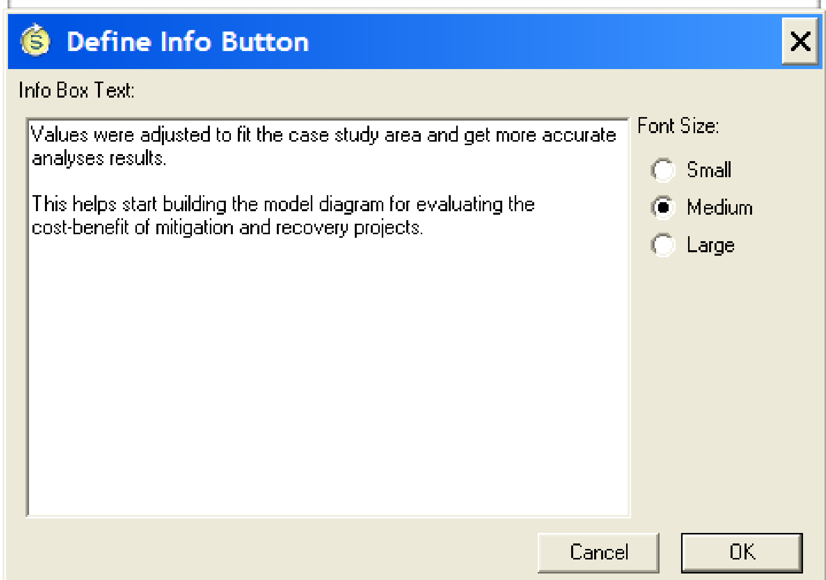


Figure 38 Defining Vulnerability Annotation





Events	Event Number	Year	Impact (US$ Million)	Adjusted Case Study Area Impact*	Adjusted Case Study Damage Assessment**
1	126	1962	21,391,487	~7,401,450.00	(843,765.81) ~ 845,000.00
2	1017	1994	8,907,958	~3,082,150.00	(351,365.50) ~ 350,000.00
3	1205	1998	3,721,100	~1,287,500.00	(146,775.07) ~ 145,000.00
4	1654	2006	3,000,000	1,038,000.00	(~ 120,000.00) 118,293.25

* Adjusted value was calculated as 34.60% as Table 2 in Appendix Y
** Adjusted value for damage assessment assumed same proportion for previous years in the order of 11.40%.

Figure 39 Analysis of Past Disasters Annotation

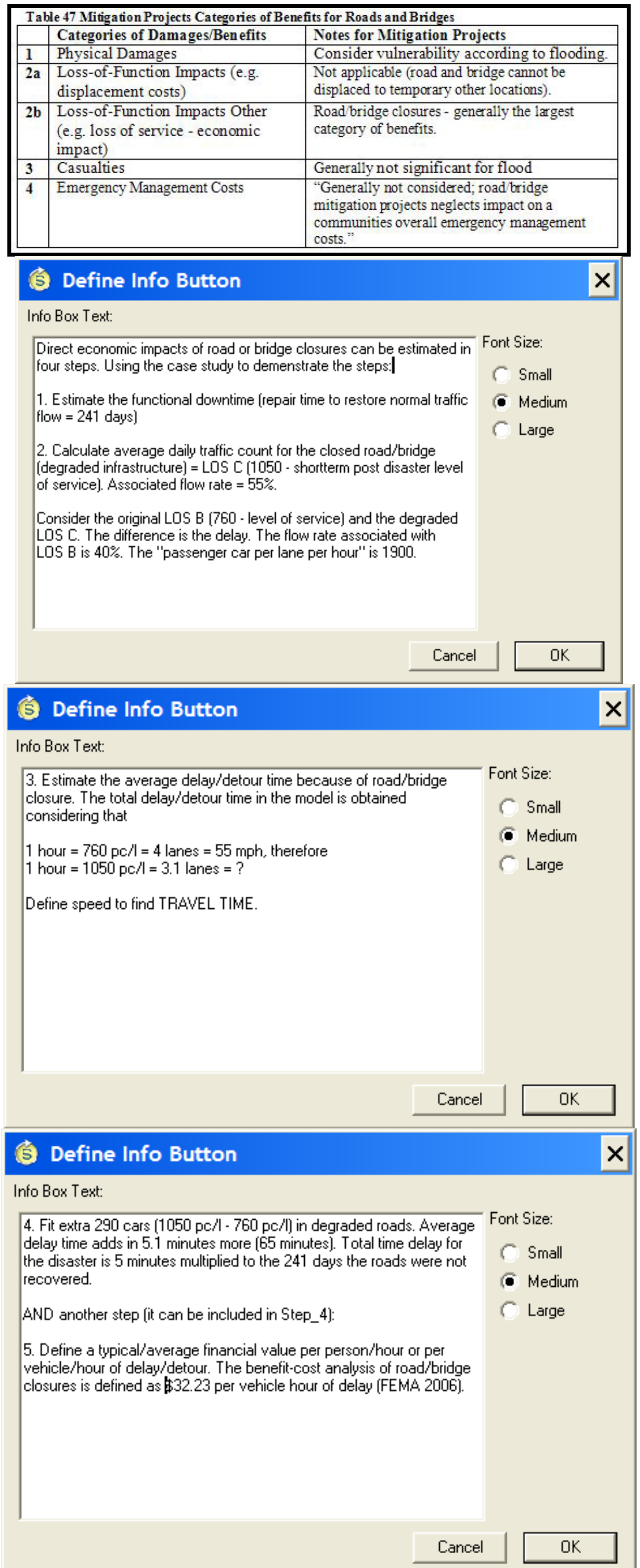


Table 47 Mitigation Projects Categories of Benefits for Roads and Bridges

	Categories of Damages/Benefits	Notes for Mitigation Projects
1	Physical Damages	Consider vulnerability according to flooding.
2a	Loss-of-Function Impacts (e.g. displacement costs)	Not applicable (road and bridge cannot be displaced to temporary other locations).
2b	Loss-of-Function Impacts Other (e.g. loss of service - economic impact)	Road/bridge closures - generally the largest category of benefits.
3	Casualties	Generally not significant for flood
4	Emergency Management Costs	"Generally not considered; road/bridge mitigation projects neglects impact on a communities overall emergency management costs."

Figure 40 Damage and Benefit Components Annotations

Table 51 Summary of the 5 Steps to Define the Direct Economic Impacts of Road or Bridge Closures

Order	Steps	Before Disaster $	After Disaster $
1	Estimate physical damages to road/bridges in dollar	0.00*	118,293.25**
2	Estimate repair time to restore normal traffic flow	0*	241 days
3	Estimate average delay/detour time	0*	(total disaster delay in days) 18,647 days
4	Obtain average daily traffic count for road/bridge	760	1050 (290 c/l/h more)
5	Calculate economic impacts of loss of function of road/bridge with the above data and the value of lost travel time ($32.23).	0.00	(total disaster delay cost) 601,006.00

* Consider value zero (0) for regular maintenance needs and related time, and existing traffic flow condition.
** Value of damage (not impact).

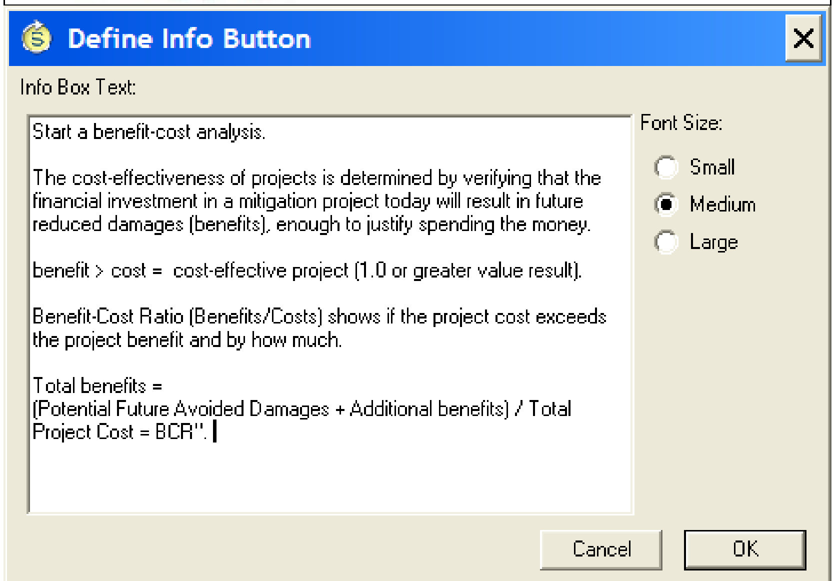


Figure 41 Cost Benefit Analysis Annotation

Table 56 Recovery and Mitigation NPV Calculations in Excel

A	B	C	D	E	F	G	H	I
	p	0.01	p	0.02	p	0.03		0.04
	Recovery	Mitigation	Recovery	Mitigation	Recovery	Mitigation	Recovery	Mitigation
0	130123	157206	130123	157206	130123	157206	130123	157206
1	1301.23		2602.46		3903.69		5204.92	
2	1301.23		2602.46		3903.69		5204.92	
3	1301.23		2602.46		3903.69		5204.92	
4	1301.23		2602.46		3903.69		5204.92	
5	1301.23		2602.46		3903.69		5204.92	
6	1301.23		2602.46		3903.69		5204.92	
7	1301.23		2602.46		3903.69		5204.92	
8	1301.23		2602.46		3903.69		5204.92	
9	1301.23		2602.46		3903.69		5204.92	
43	1301.23		2602.46		3903.69		5204.92	
44	1301.23		2602.46		3903.69		5204.92	
45	1301.23		2602.46		3903.69		5204.92	
46	1301.23		2602.46		3903.69		5204.92	
47	1301.23		2602.46		3903.69		5204.92	
48	1301.23		2602.46		3903.69		5204.92	
49	1301.23		2602.46		3903.69		5204.92	
50	1301.23		2602.46		3903.69		5204.92	
	$148,080.95	$157,206.00	$166,038.89	$157,206.00	$183,996.84	$157,206.00	$201,954.78	$157,206.00

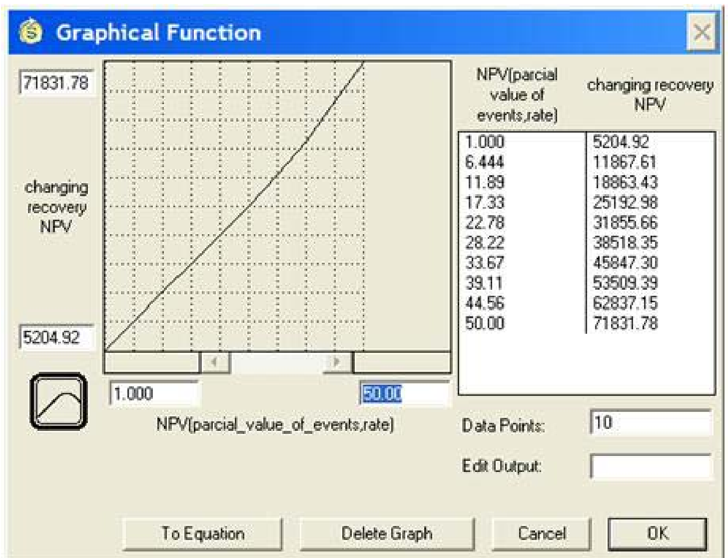


Figure 67 Graphical Function for Recovery Project NPV

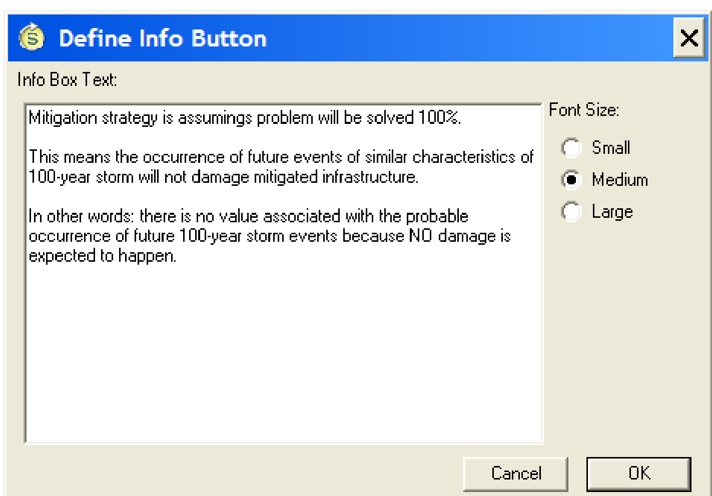
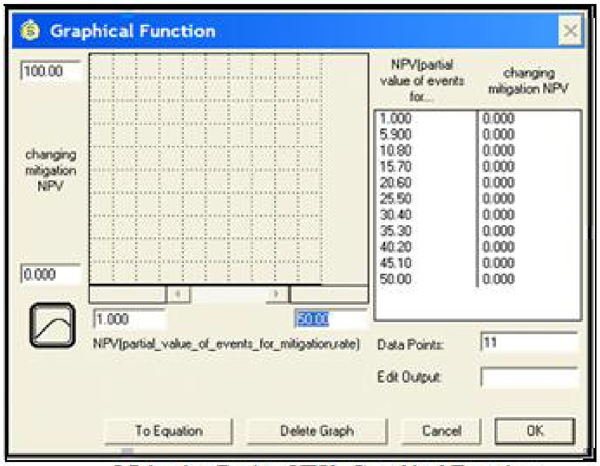


Figure 42 Net Present Value Calculation Annotation



Mitigation Project NPV Graphical Function

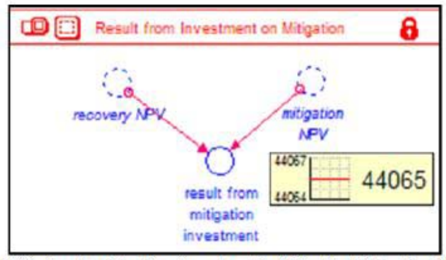


Figure 69 Savings Resulting from Investment in Mitigation Rather than Recovery

Table 62 Summary of Benefits for Recovery Projects

Net Present Value of Future Benefits • Possible repetition of damage to mitigated infrastructure (no certainty of extent of damage possible to be bigger and/or smaller, despite physical conditions improvement) • Possible repetition of Loss of Function - services value not being provided due to damage (total disaster delay cost) • Improved road condition (1% - average IS recovered condition) *Total:*	($118,293.25) ($601,006.00) 1% x(118,293.25 + 601,006.00) *($23,042.00)*
Recovery Project Costs (total lanes recovery cost)	$130,123.00
Benefit-Cost Ratio (Net Present Value of Future Benefits ÷ Project Costs)	**-0.18**

Table 64 Benefit-Cost Analysis Comparison Summary for Recovery and Mitigation Projects

SUMMARY (all NPV)	Project Cost	Benefits (avoided damages and losses)	Cost-Effective	BCR
Recovery	201954	-23042	NO (-23042 < 130123)	-0.18
Mitigation	157206	719299	YES (719299 > 157206)	4.6

Figure 43 Summary Results

6.3 <u>Presentation Tool</u>

The interface includes a “presentation” tool that is able to run different scenarios. The final interface is shown in Figure 43. The interface gives the user control of the model (Run, Pause, Stop), control of the sensitivity analysis, access to instructions, and the “story” describing the model.

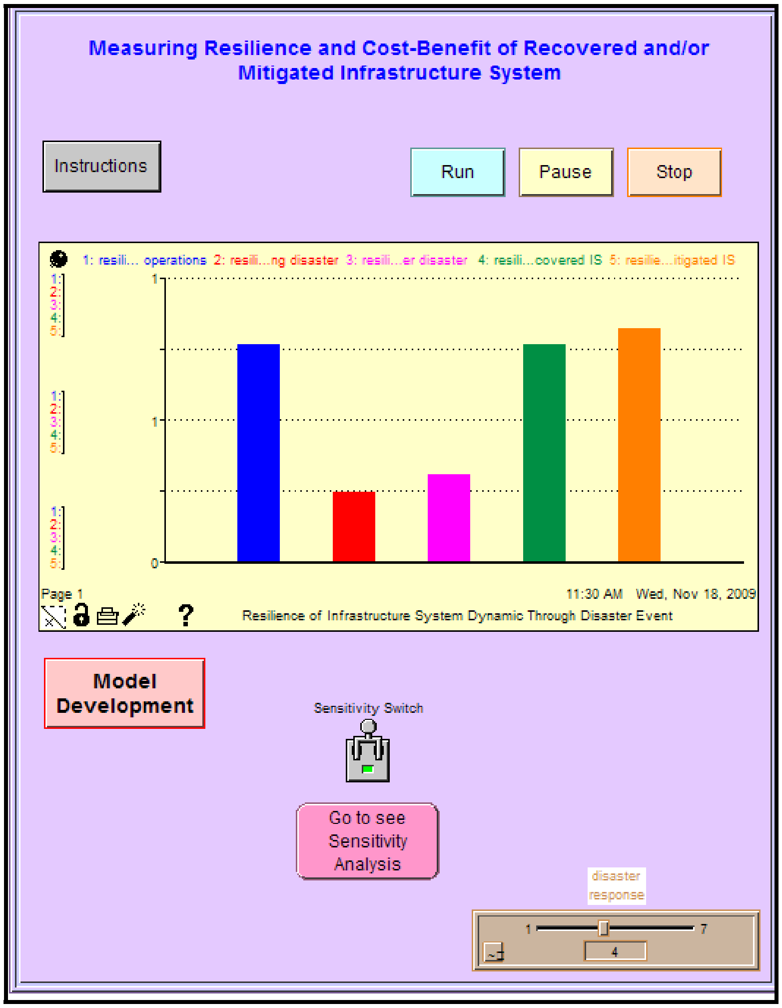


Figure 44 Final CIR-DSS Management Information System Model's Interface Page

CHAPTER 7 MODEL RESULTS AND EVALUATION

7.1 Results

Running the model in STELLA produces an assessment of the resilience of the system and the impacts (costs) for six different scenarios. These scenarios are a subset of the following conditions and choices:

- Infrastructure projects (the decision variables in this implementation)
    - Recovery only
    - Recovery and mitigation (mitigation is developed building over earlier developed recovery projects)
- Probability of a 100-year storm event in the case study area
    - 1%
    - 4%
    - 8%
- Time required for a disaster response
    - 2 days
    - 4 days

The model results, as shown in Table 12, show the difference between the net present values of recovery projects minus the net present values of mitigation projects. The results are also shown in Figure 45. The variable names “recovery NPV” and “mitigation NPV” are based on a 4% event probability. The variables “recovery NPV 2” and “mitigation NPV 2” are based on a 1% event probability. The variables “recovery NPV 3” and “mitigation NPV 3” are based on an 8% probability. However the last mitigation variable is not included in the graph due to display limitations in STELLA. This does not impact the results because the net present value of mitigation is shown to be a constant.

Table 12 Difference of Project Costs Considering Different Event Probabilities

Probability of 100-year storm event	Variables	Result	Impact
1%	Recovery NPV2 – Mitigation NPV2	-$9,809	Recovery costs less than mitigation
4%	Recovery NPV – Mitigation NPV	$44,065	Recovery costs more than mitigation
8%	Recovery NPV3 – Mitigation NPV3	$115,896	Recovery costs more than mitigation

The higher the frequency of the 100-year storm event the more worthwhile investments are in mitigation projects. The sensitivity analysis considered changes in the value of damaged infrastructure, and its impact on recovery and mitigation projects to fix the damaged infrastructure. Initial results (Figure 45) are based on the damage resulting from the June 2006 flood, and the calculated cost of recovery and mitigation projects for the different disaster frequencies. The “damaged IS” is an input variable in the model.

The frequencies of disaster were chosen based on existing records of similar past disasters, although the record does not cover a 100-year period but just half of this period. While current frequency is about four (4) 100-year disasters (flooding), because there is another half century over which other 100-year storm may occur, it is possible to imagine that another four (4) disasters of similar type can happen. In other words, while the frequency is 4% for the 100-year storm frequency, it can be expected that another 4 events can happen changing the frequency to 8%. The damage determines the final cost of projects and amount (US$) of benefits or avoided damage and disruption. The variable “damaged IS” of “131437” (US$), is based on:

- the addition of 10% (US$ value) avoided damage because of an existing warning system shown in the model development working paper (Croope 2010a),
- the original resized/resample case study area (34.6% from the total reported value statewide), approximately 118,000 (US$).

The damage value used to test the model was marked to change for 3 runs from $131,437 to US$50,000, US$275,000, and US$500,000. The graph type chosen for display was again the bar chart because it holds up to 5 variables showing the impact of changing the damage values.

The “y axis” represents the NPV (net present value) of recovery and mitigation, which changes with the different simulation runs. For example, “recovery NPV 3” has a value of $273,786 (U.S.) which matches bar height on the “y axis”.

With the sensitivity analysis turned off, the results are shown in Figure 44. This is the output using the original values included in the model. Each bar represents the net present value of recovery or mitigation project costs calculated for the different probability of events. The bars corresponding to “mitigation NPV” and “mitigation NVP 2” do not vary since the net present value of project costs is constant. Now looking at the benefits associated with mitigation projects, they are more significant as the probability of a 100-year storm increase, as shown in Table 12.

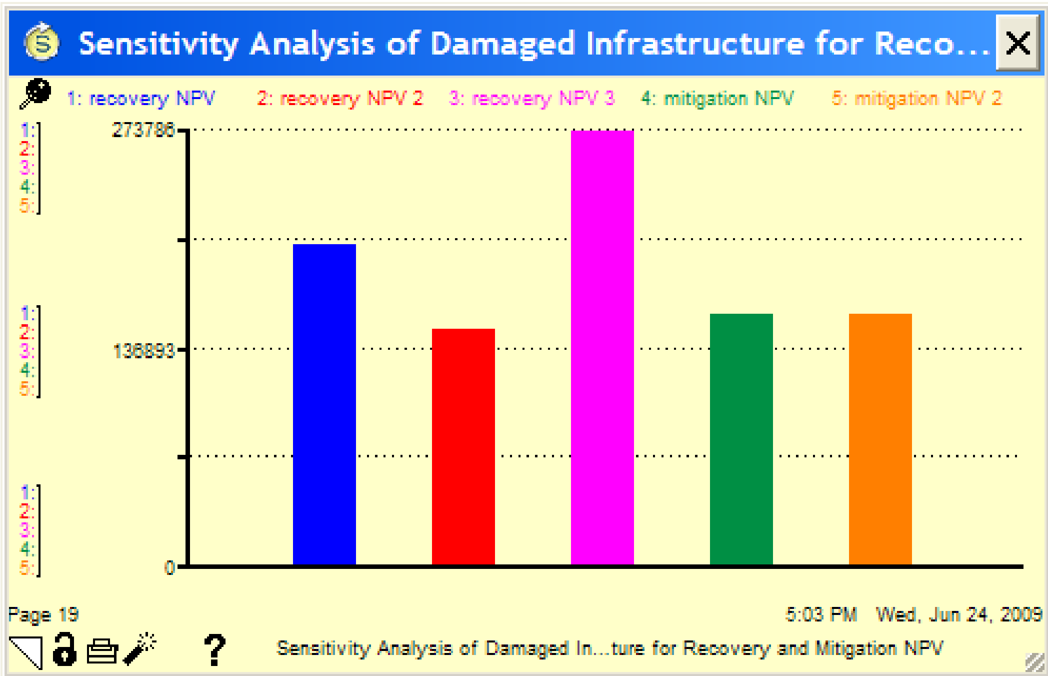


Figure 45 Results Without Sensitivity Analysis

Similarly Table 13 shows the results for two scenarios – one with 2 day response time, the other with a 4 day response time – assuming a 1% probability of a 100 year flood event. As expected the longer the recovery time, the greater the impact.

Table 13 Model Results by Using the Switch Button for 1% Event Probability (thousands)

Variables	**NPV**	
	2 days Disaster Response	**4 days Disaster Response**
recovery NPV 2	$148,000	$512,900
mitigation NPV 2	$157,900	$600,6
Benefit from mitigation investment 2	-$9,800	-$87,700
loss of function for recovery NPV 2	-$1,500	-$2,500
loss of function NPV 2 (mitigation)	$719,300	$1,218,000

As described in Section 5.2 we are interested in tracking the resilience of the systems over time. Rather than a continuous representation of the resilience as show in Figure 27 and

Figure 28, and also shown in Figure 82 in the working paper "Model Development in STELLA" in Croope (2010a), five snapshots show the resilience over time. These snapshots are based on the following time frames:

- Pre-disaster
- During the disaster
- Immediately after the disaster
- During recovery
- Post-disaster

Using the three measures of resilience (carrying service capacity, physical condition, and level-of-service) defined in Section 6.3, Figure 46 to Figure 48 show the changes in these resilience component measures for each of the four time periods in the scenarios outlined above. The figures showing the capacity and flow rate include both normalized and absolute values. These figures are similar to the reference behavior patterns shown in Figure 27 and Figure 28.

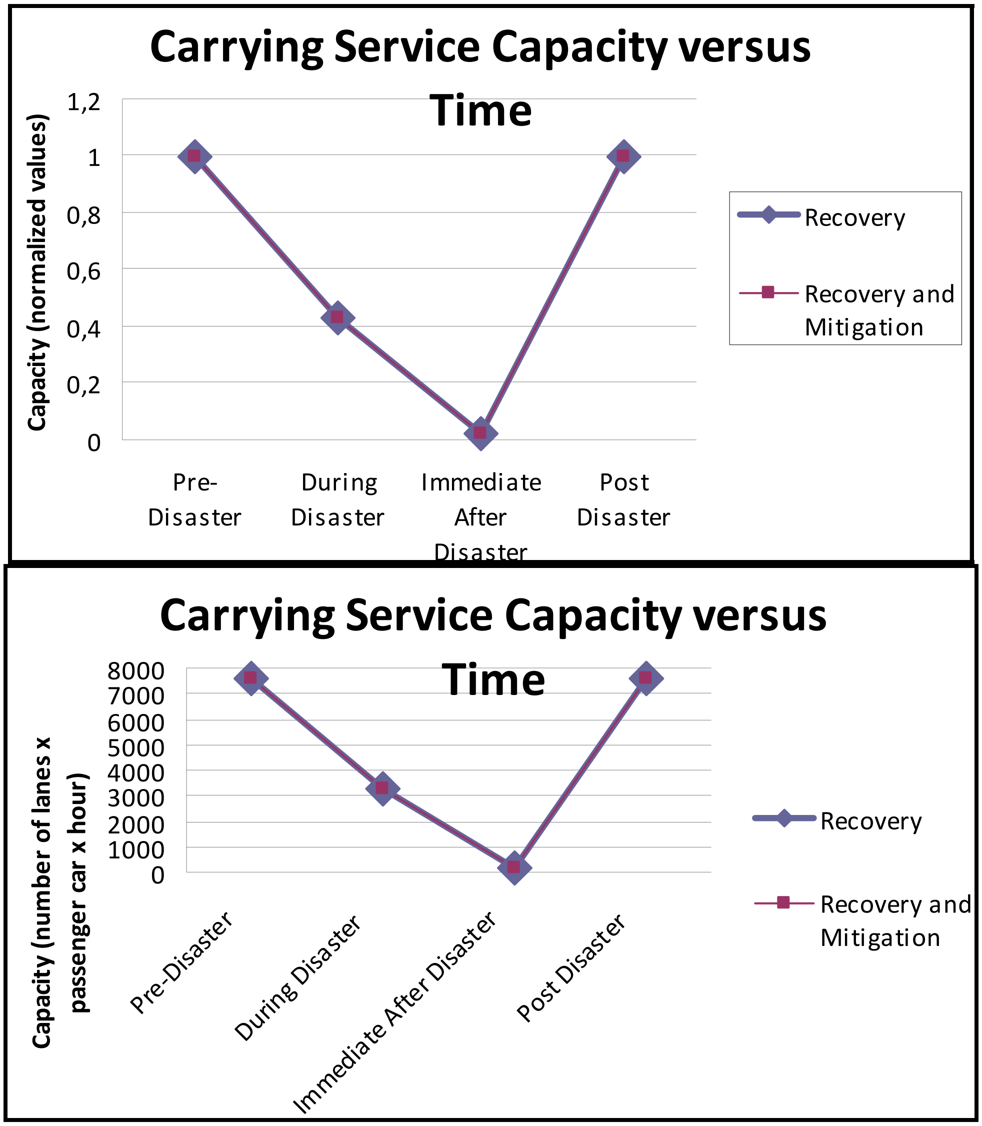


Figure 46 Changes in Resilience: Average Capacity - Over Time

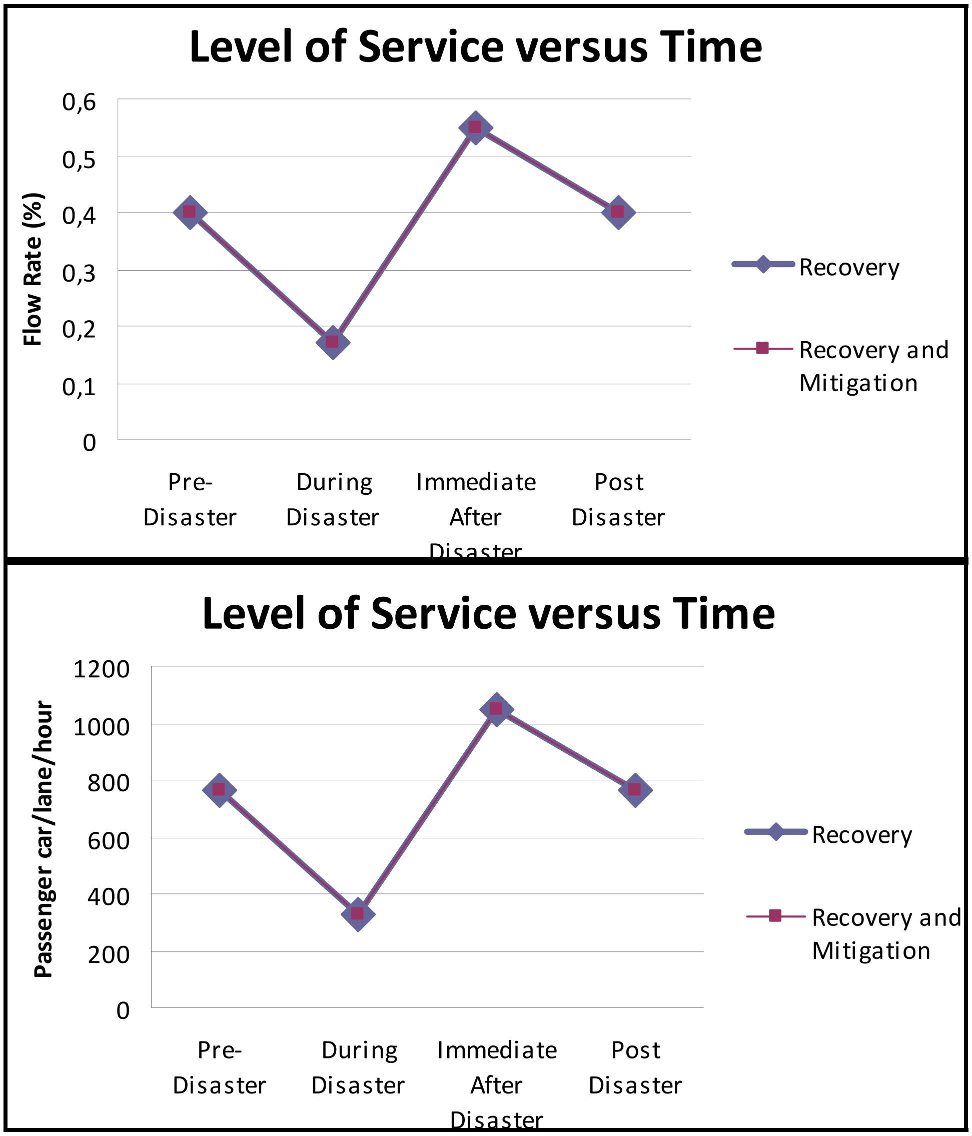


Figure 47 Changes in Resiliency: Flow Rate and Traffic Use of Highway over Time

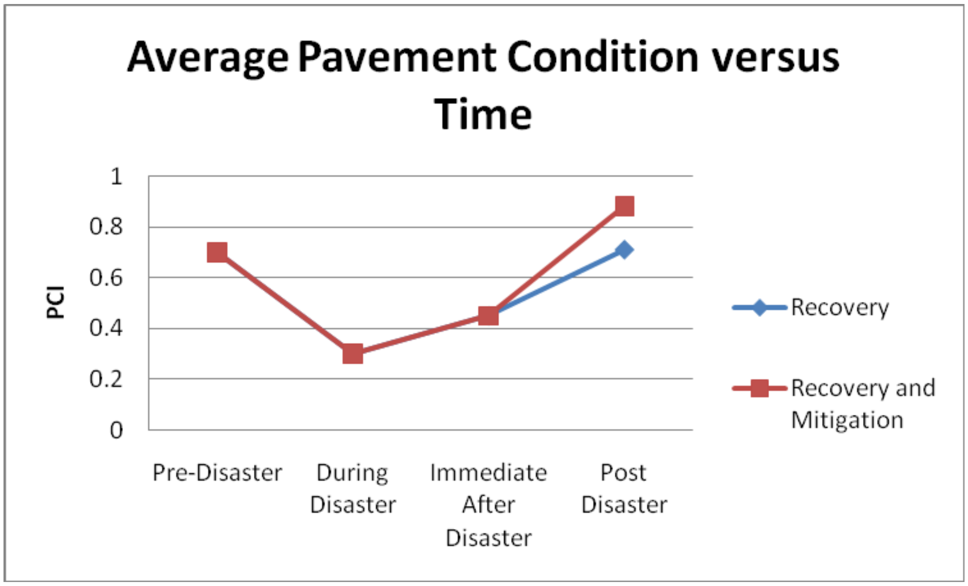


Figure 48 Changes in Resiliency - Average Pavement Condition - Over Time

In all cases, recovery and mitigation, at a minimum, restore system to its original values. Because of the type of mitigation measures chosen, the infrastructure physical condition is the most sensitive measure, improving the infrastructure system for both recovery and mitigation, and impacting the overall system performance and resilience.

Although disruption is another measure used to capture resilience, for the pre-disaster and post-disaster states, disruption has no significance, therefore this is not a variable that is consistently measured and it is not shown in graphs. Disruption is null for before- and post-event, but present during “hazards onset”. The post-event measure with respect to disruption is damage. The consequence of which may include traffic detours which are then accounted for in the evaluation of economic and social impacts.

Different probabilities of 100-year storms frequency may cause the infrastructure system physical condition to slowly shift the initial “PCI” (0.7) to a PCI that represents a better condition roads (e.g. PCI = 0.9). Consequently, physical condition and mitigated impacts push the value of resilience higher (e.g. resilience of 0.77 to 0.78 and so on) as shown in Figures 79 and 80 in the Model Development Working Paper (Croope 2010a).

The damage to the infrastructure due to a disaster, relates to the different performance and condition measures. Nevertheless, depending on which mitigation measures are adopted, one or all measures that build upon resilience may improve.

Another look at changes in resilience is an analysis of vulnerability. Vulnerability was specified as a function of impact minus the adaptive capacity (Section 2.4). Figure 48 shows the value of initial vulnerability, and the vulnerability after recovery and mitigation strategies. The decrease in vulnerability shown (Figure 49) is also an improvement in adaptive capacity related to the improvements on infrastructure physical condition.

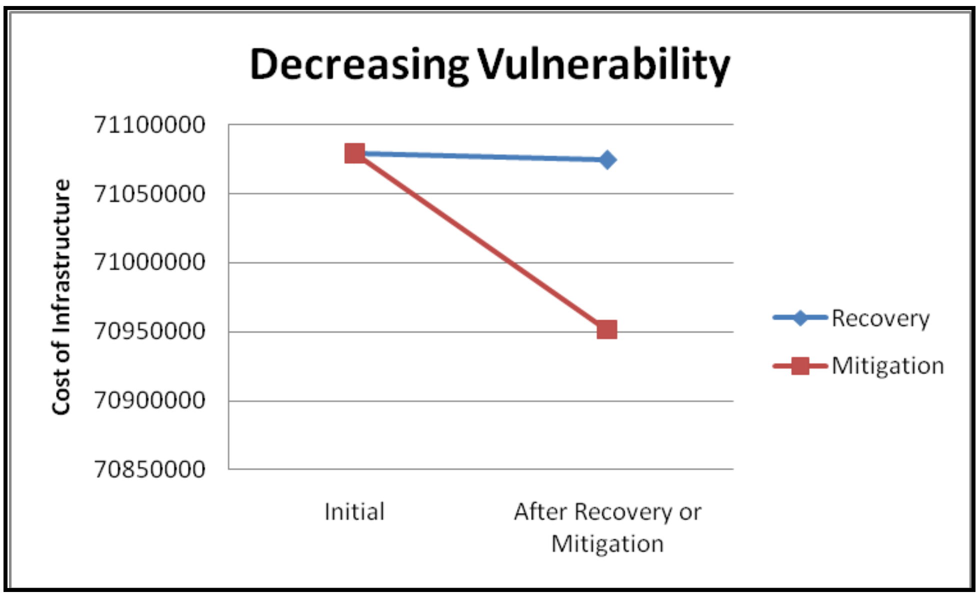


Figure 49 Decreasing Vulnerability

Looking at Figures 46 to Figure 48, it is easy to understand such vulnerability. The improvement in adaptive capacity is building more robustness into the system. Redundancy is not observed for the infrastructure network when adopting mitigation strategies that only address improvements to physical condition.

7.2 Sensitivity Analysis

Using the parameters defined in Section 5.12, the results of the sensitivity analysis for damage of $500,000 are shown in Figure 50. Comparing Figure 50 with Figure 45, the worst scenario is to only undertake recovery (not mitigation) when there is an 8% probability of a 100-year storm in the case-study area.

When the sensitivity analysis is "on" the value of damage varies. Recovery projects require more expensive projects when the damage is higher. When comparing recovery to mitigation, bigger savings are realized if an investment in mitigation projects is selected in the case of higher event probabilities. Looking at "recovery NPV 3", projects for an 8% event probability cost over $638,664 (US$). Mitigation projects also became more expensive as the "optimum" result for event frequency rise above the 4% probability, but was less than the 8% event probability. This shows that mitigation strategies prefer high event probabilities, and the initial graph showing that a 4% event probability is not universally an optimal point for choosing mitigation instead of recovery projects. Considering the decision on a case-by-case basis involves determining that mitigation can be the best choice for high frequency events.

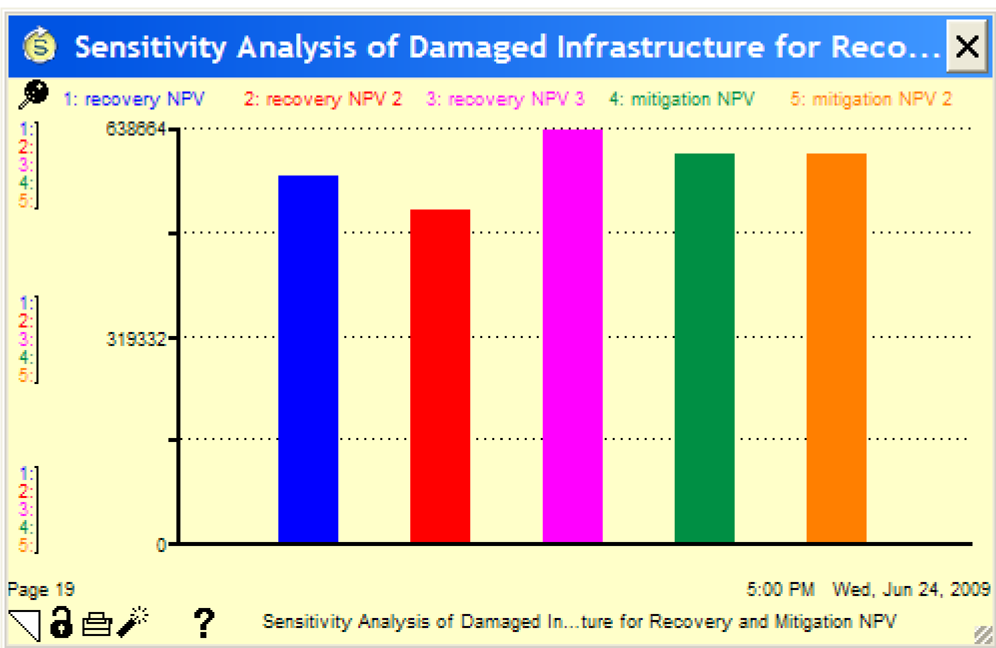


Figure 50 Results of Sensitivity Analysis for Damage of US $500,000

Each run generates different graphs and values as damage value changes. Mitigation projects as the optimum solution (defined as the least cost solution) changes along with different values of damage. The changes are shown in Figure 45 and Figure 50 to Figure 52. These figures, also illustrate why it is so important to have good quality data, include key decision-makers and key variables. Table 14 summarizes mitigation projects values according to damage.

Table 14 Sensitivity Analysis for Different Damage Values and Event Probabilities

Damage	Recovery Projects	Mitigation Projects
~$131,400	Best for 1% event probability	Best for event probability of 4% and above
$500,000	Best for 1% or 4% event probability	Best for event probability of 6% and above
$50,000	---------	Best for 1% event probability and above
$275,000	Best for 1% event probability	Best for 3% event probability and above

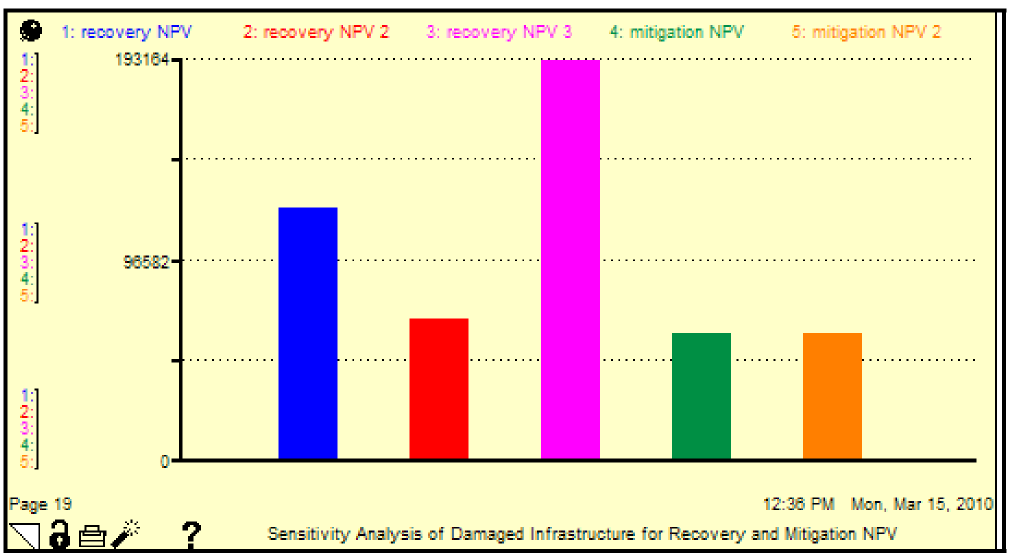


Figure 51 Sensitivity Analysis for Damage of US$50,000

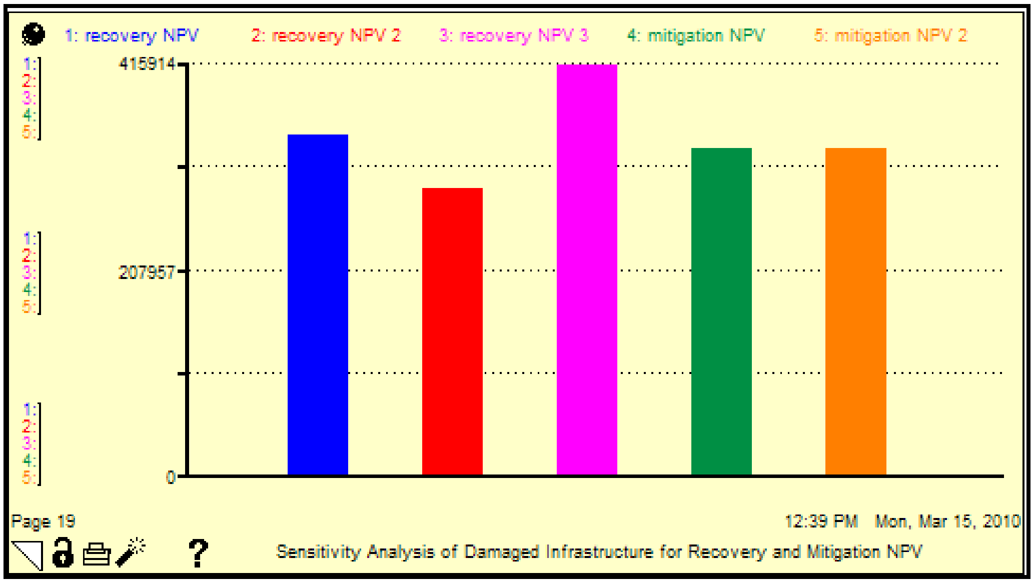


Figure 52 Sensitivity Analysis for Damage of US$275,000

These different recovery or mitigation NPV values along with resilience results reflect the impacts of different decision variables that relate to the type of projects (recovery or mitigation) that stakeholders must choose.

Changing the damage value does not change performance measures or resilience. Change in damage value impact on recovery and mitigation Project Net Present Value only. Damage value is only one input of many needed to properly calculating performance measures and resilience.

7.3 Discussion

In this case study, mitigation is advantageous when the observed frequency of a flood, if above 4%, is most likely when there is more than 7% of a 100-year storm in a 100-year period. In reality the historical frequency of disaster events for the study area is greater than 4%. If considering just the similar types of events, it is important to recognize that the recorded events used in the simulation do not cover the period of 100 years only, so there is time for similar disasters to take place. In more precise terms, the period analyzed covers about 45 years.

This means the historical trend is definitely important, and places with a high frequency of hazardous events are well-advised to adopt mitigation from an economic perspective more than locations with a small frequency of hazardous events. Nevertheless the trade-off then becomes safety and security with less loss of lives versus the most beneficial use of money. Other social factors (e.g. death compensations) with financial impact can definitely make the difference and support pro mitigation. Current model results show it is important to analyze, case-by-case, individual disasters taking advantage of historical records to have a more accurate analysis result. Also it is important to carefully choose and measure potential benefits of recovery and mitigation projects.

CHAPTER 8 CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This research developed the Critical Infrastructure Resilience Decision Support System (CIR-DSS) framework to improve the resilience of critical infrastructure systems. The framework for the CIR-DSS consists of interconnected analyses that provide information for decision-making considering:

- the sequence of events and disruption caused by a disaster (response, recovery, mitigation);
- the range of possible decisions relating to mitigation recognizing the economic trade-offs that are featured using asset management principles, and performance measures that evaluate system resilience; and
- insights into the opportunities for improving the resilience of the infrastructure system.

Developing this complex modeling system required many assumptions and models to show the changes in the system over time. In addition, data from many sources including GIS analysis and the HAZUS-MH software was used as inputs into the model. The comprehensive picture developed offers several insights into the tradeoffs and opportunities involved in systematically portraying the damage and costs of resiliency. Further refinements are needed to operationalize this approach and are documented in the following section. The following chapter also documents the contributions of this research.

This research set out to answer the question "*How is the resilience of critical infrastructure systems improved using information and decision support systems?*" The development and application of the CIR-DSS showed that the resilience of the system can be improved by making specific investments in mitigation strategies.

8.2 Future Research

This research identified several areas that need further investigation. These specific topics can:

- improve the analysis of other aspects of management of critical infrastructure systems through the inclusion of other elements and more elaborate models,
- help understand and address current issues in a variety of disciplines, and
- evolve the tool to technologically user-friendly tools/software enabling further in depth consideration of real-world complex problems.

Suggestions for future research include:

- the application and enhancement of the model to question policy effectiveness and evaluation
- the application and enhancement of the model to question the adoption of different discount rates (FEMA vs. FHWA), its importance when looking at real-world practices
- the investigation of the use of other specialized asset management models to improve asset management analyses and in depth results
- the exploration of other recovery and mitigation strategies and including them in the model in STELLA
- the development of the part of the model that shows resilience improvement through time, exploring the spiral development concept
- the making of a comparison over time and with overall results between the current FEMA processes for recovery and mitigation strategies. This includes the current framework and model, an evaluation of the selection process, and a proposed framework to develop:
    - better comprehensive strategies
    - evaluation and validation of the process's steps

    - better analysis results (completeness, accuracy after using customized data in the CIR-DSS)
    - compact and visual communication of the results
    - time for populating data into the system after all processes are understood and data is made available
    - contributions and limitation of this approach
- the research of alternative resilience measures
- the exploration of the mitigation strategy (threshold) of “moving out” of the path of frequent location damage, such as an abandonment of specific segments and the construction of new segments as an alternative to the problem, not an alternative route
- the provision of an opportunity for the U.S. government infrastructure and emergency agencies to use this research as means of leveraging integration efforts and optimizing the use of current limited resources eventually required by all 50 States for recovering from disasters.

CHAPTER 9 CONTRIBUTIONS

This research contributes to the state-of-art knowledge in Civil Infrastructure Management and Disaster Mitigation (preparedness). With increased interest in disaster preparedness (mitigation) following the attacks of 9/11, Hurricane Katrina, the degrading of civil infrastructure conditions, limited resources for mitigation, and infrastructure replacement, CIR-DSS is a unique tool. The tool demonstrates the complexity of the decision making process, the integration of concepts of resilience into the decision making process and the value of a systematic process. The most important contributions are presented in three areas:

A. Model/framework development
B. Model implementation, and
C. Model results.

9.1 Model/Framework Development

The model/framework developed:

1. Demonstrates the use of a multidisciplinary approach integrating scientific knowledge and current practices in managing CIS resilience issues
    - integrates data, information and knowledge from sociology, geography, political science, administration, and civil engineering
2. Proposes a simple way to include and integrate variables of different natures into the complex problem model
3. Bases the development of the framework for managing critical infrastructure systems on state-of-the-art research and real-world experiences

9.2 Model Implementation

The implementation of the model:

1. Underscores the importance of data and information sharing among agencies - a current issue needing further investigation and practice
2. Develops, evaluates, and validates a DSS based on system dynamics for managing civil infrastructure systems. This complex system, when stressed by disasters, requires the consideration of agency and user perspectives that are accounted for in:
    - the framework conceptualization, and model development simultaneous with a case study simulation using existing and theoretical data, and
    - the evaluation of the framework results
3. Uses principles, concepts of resilience, and defining resilience metrics to analyze resilience in CI systems (e.g. transportation corridors). Resilience is integrated into the decision-making process for managing CIS challenged by disasters
4. Uses system dynamics to model complex problems. This enables data/results verification, analysis adjustment according to feedback loops/necessary inputs for defining options, and choosing among recovery and mitigation strategies
5. Uses qualitative/quantitative approaches to integrate the (project) tactic to a strategic level, aggregating and interpreting analysis results, and helping to support decisions by translating qualitative information into quantitative data
6. Considers the need for using a flexible format to adjust for new/changes in variables, policy, different decision-makers' interests, new parameters for more analyses, substitution of equations, and more. This recognizes real-world dynamics and

- enables the model to generate either optimal analyses results or feasible analyses results working with either theoretical or practical (real-world) values
- supports the simulation of different scenarios and looks at their effectiveness (optimal results vs. feasible/desired results)

7. Integrates operations dynamics of management activities and vice-versa.

9.3 Model Results

The model results:

1. Provide a mechanism to observe concepts, principles and phases of disaster, integrating current governmental practices related to disasters with general asset management principles and governmental practices
2. Give insights for recovery and mitigation strategies focused in resilience of system improvement (enhanced approach to current practices) that also considers financial trade-offs
3. Give insight into how to use different FEMA policies for recovery and mitigation to decrease the time required to restore an infrastructure to "normal operation", with improved resilience of the infrastructure system
4. Help identify short/long-term actions/projects as part of recovery and mitigation strategies by defining project priorities considering the potential impacts of disasters on infrastructure operation and management
5. Illustrate the use of parametric analysis in CIR-DSS to explore the impacts of decisions during the different phases of a disaster
6. Demonstrate the use of road infrastructure condition and performance data, both real-world and hypothetical data for pre- and post-disaster analysis
7. Help identify opportunities for improving model flexibility.

APPENDIX A - TERMINOLOGY

Infrastructure system is related to how it performs, not all physically connected to the structure it serves (e.g. mail delivery, fire fighting), where many physical infrastructures aren’t shared by multiple applications either (Robertson and Sribar 2006).

Critical Infrastructure systems refer to those infrastructure elements in dependent systems or organizations, which if damaged or destroyed, could cause serious disruption. The systems therefore play a key role in the Nation’s economy and security and must be protected from disruption of service at all times. Service disruption occurs when one or more of the infrastructure’s physical components and/or associated activities cannot operate at prescribed levels resulting in the inability to meet demand - service is degraded (Mendonça and Wallace 2006).

Some types of infrastructure are related as components of systems. According to the 1997 United States President’s Commission on Critical Infrastructure Protection (President's Commission on Critical Infrastructure Protection 1997), there are eight infrastructure systems that are life support systems (e.g. transportation). To regulate and create mechanisms to deal with disasters, the United States has created government agencies such as the Federal Emergency Management Agency – FEMA, and the Department of Homeland Security – DHS (CNN.com 2002; Wikipedia contributors 2007e).

Disasters are socially consensus defined occasions in a complex world of linkages, chains, and processes involving radically changing behavior to meet a crisis, analyzed empirically, mathematically and logically, throughout the natural and built environment. Disaster is the result of possible rapid and in depth event strikes with significant damage, disruption, destruction and losses of life that impacts socioeconomic systems, and shocking peoples’ perception of normal daily life. It requires people and organizations to evolve and adopt, prepare, respond and rescue, recover, and take mitigation actions for the future continuity of life. The adoption of concepts is important because they can affect social organizations in several ways, including the inclusion or exclusion of social layers (e.g. poor people and social assistance), and the distribution of funds and grants (e.g. magnitude of disaster) (Rose, Unknown). Also the understanding of the use of the current temporal stages used in the disaster cycle and in emergency management: preparedness, response, recovery and mitigation (Gow, 2003) have an important role in this research, which is the definition of boundaries to focus the research analysis.

In the United States, the scale of disasters is used by the Federal State of Emergency (office) as a mechanism to distribute help and financial assistance to respond to, recover from, rebuild on, and prepare against a disaster. Impacts of a disaster can refer to the strength of the disaster in terms of seismic vibration, wind speed, etc. Impacts have been based on the total of debris, the sum of money to clean, personnel training and rebuilding, and service demand. If the scale of disruption and damage suffered is very extensive, it may compromise the socio-economic conditions and make difficult or impossible recovery and continuity. Economic system facilities represent a big loss of resources and/or production to society. The cost evaluation is difficult to establish due to poor quality or lack of relevant data. Therefore vulnerability assessment, damage assessment, critical infrastructure physical condition, and network evaluation must all be brought together for the resilience of system analysis.

In a disrupted system, recovery activities would focus and reflect services in high demand, construction under temporary and/or permanent fix, and making the infrastructure operable. Mitigation would include reconstruction activities where some systems would be already working. Disrupted complex infrastructure, which represents big investments, would be under evaluation, planning activities and construction, including the adoption or not of resilience measures.

<u>Vulnerability</u> is a measure of susceptibility to suffer loss or damage. Where higher resilience reflects less likelihood of damage, faster and more effective recovery, higher

vulnerability means a more exposed "community, group, individual, or nation to loss and damage" (Doherty, 2006). Vulnerability can be defined as the human product of physical exposure to a disaster resulting in some degree of loss and considering the human capacity to withstand, prepare for, and recover from that event (Dalziell and McManus 2004). Vulnerability of a given natural or human system depends on the adaptive capabilities of the system and its effective impact coping potential and the risk associated with it (Bhadwal Unknown). Infrastructure is vulnerable to geographic hazards such as natural disasters, epidemics, and some types of terrorist attacks. Geographic disruption often affect infrastructure in proportion to the size of the affected area. A disruption of concentrated infrastructures, in close physical proximity to each other, can have a disproportionate and national effect (Moteff and Parfomak 2004). Vulnerability and failure are components to be addressed whenever the goal is the evaluation and enhancement of systems to propitiate a smoother flow condition for critical infrastructure systems. Lessening vulnerability and failures may help to improve the resilience of systems. Mitigation, vulnerability, and failure are key terms to understanding and addressing resilience for systems.

Mitigation is an action taken over the long-term to improve preparedness or response measures through research, by improving weather forecasting or building new weather alert systems, developing a sustained program aimed at improved recovery procedures through new forms of insurance and loss coverage, or by other means (Altay and Green III 2006). Mitigation activities, according to the Department of Homeland Security – FEMA, must provide value to North-Americans reducing loss of life and property and creating safer communities (FEMA 2007d). It includes hazard mitigation including measures to reduce casualties and exposure to damage and disruption, providing passive protection during disaster impacts, or before a disaster (e.g. land-use regulations) (Tierney *et al*. 2004).

Failure is a "state or condition of not meeting a desirable/intended objective" which usually leads to collection and analysis of data to determine its cause and allow for improvements (Wikipedia contributors 2007b; Wikipedia contributors 2007c). Failure in critical infrastructure systems must be analyzed by looking at continuity of operation and flow. Disaster likelihood and risk factors also play a part in the failure studies approach of common cause failure resulting from disaster impact (Burden 2007). Interdependent critical infrastructure systems failure dimensions are classified in three categories; cascading, escalating, and common cause. Common cause is the name given to a failure originated by natural disaster (Kelly 2001). Failure of a critical infrastructure system impacts and damages a nation's socio-economic structure leaving a bad legacy for future generations, where recovery may not be possible. Failure in a system of systems perspective transfers the holistic and complex approach of interconnected, interdependent, and vulnerable systems to disasters. These two types of failures are the ones focused on this research where the resilience improvement process of critical infrastructure systems is the main goal.

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