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**CENTER FOR MULTIMODAL SOLUTIONS FOR CONGESTION MITIGATION
(CMS)**

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CMS Project Title: Development of a Multimodal Transportation Educational Virtual Appliance

(MTEVA) to Study Congestion during Extreme Tropical Events

for period __8/1/2009__ to __7/29/2011__

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TABLE OF CONTENTS

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LIST OF TABLES

ABSTRACT

In this study, a prototype Multimodal Transportation Educational Virtual Appliance (MTEVA) is developed to assist in transportation and cyberinfrastructure undergraduate education.   This initial version of the MTEVA provides a graphical user interface (GUI) to a modeling system which couples a storm surge and inundation model with congestion models for emergency situations in a simple hypothetical domain. As part of the development process, a preliminary suite of educational content is developed based on interactive simulations which can be performed using the coupled system. Finally, a group of graduate students is surveyed about their attitudes about the MTEVA. Analysis of the survey responses showed that the participants believe that the MTEVA significantly aids in their understanding of key science topics: storm surge and inundation, optimization and transportation engineering.

EXECUTIVE SUMMARY

The top priority for emergency managers before, during, and after an emergency situation is to provide safe and efficient transportation routes. In the coastal areas of many southeastern states along the Gulf and Atlantic coasts, this priority is complicated by the inherent combination of multimodal transporting methods and choke points defined by water barriers and the bridges and tunnels built to surmount them. Furthermore, in many of these coastal areas, extreme tropical events can render ports (due to high waves), bridges (due to extreme winds) or roads (due to flooding) unusable, completely reconfiguring the transportation network. Combining these infrastructure issues with the unpredictability of human behavior of both native residents and coastal tourists alike leads to significant challenges in the study of multimodal congestion mitigation in coastal communities during extreme events (non-recurrent congestion).

To deal with these challenges, two different groups within the academic community are tackling the problem. In one group, meteorologists and coastal scientists are developing advanced atmospheric and estuary models to simulate the natural environment during a storm. In another group, optimization experts are developing congestion mitigation models to plan the most efficient routes. In this study, these two groups are working together to create a prototype virtual environment for interdisciplinary research and education. In this environment, an example of how these models can be coupled is presented through an interactive demonstration. This demonstration helps educate future generations of scientists and engineers as well as provides outreach to the general public. This collaborative research environment facilitates interdisciplinary scientific discovery among these two groups through model integration and provides access to a world-wide "Grid" of computing resources. Finally, although only a couple of educational lessons are available, the environment is easily expandable such that additional applications and educational content can be added.

Specifically, in this study a prototype Multimodal Transportation Educational Virtual Appliance (MTEVA) iss developed to assist in transportation and cyberinfrastructure undergraduate education. This version of the MTEVA provides a graphical user interface (GUI) to a modeling system which couples a storm surge and inundation model with congestion models for emergency situationsin a hypothetical domain. As part of the development process, a preliminary suite of educational content is available based on interactive simulations which can be performed using the coupled system. Finally, a group of graduate students is surveyed about their attitudes about the MTEVA. Analysis of the survey responses showed that the participants believe that the MTEVA significantly aids in their understanding of key science topics: storm surge and inundation, optimization and transportation engineering.

1. BACKGROUND

Hurricanes, earthquakes, industrial accidents, nuclear accidents, terrorist attacks and other such emergency situations pose a great danger to the lives of the populace. Evacuation during these situations is one way to increase safety and avoid escalation of damages. The penalties incurred when Hurricane Katrina caught the nation off guard were severe. It is estimated that Hurricane Katrina displaced more than 1.5 million people and caused economic damages of $40-120 billion (DesRoches 2006). Such disasters are well documented, allowing better preparation for future extreme events. Over the past decade, evacuation problems have been given a heightened attention and there are numerous studies available in the literature on evacuation strategies (Wolshon et al. 2005; Gwynne et al. 1999; Kuligowski and Peacock 2005; Santos and Aguirre 2004; Bryan 2000; Radwan et al. 2005).

Models currently available in the literature are usually customized for the evacuation of specific geographic regions. The models have their relative advantages and disadvantages, but are customized to their specific needs. It is rather tedious to generate a unified model that can be used in all situations. Inclusion of several features impacts the complexity of the model and hence the computational speed. On the other hand, simplifying a model compromises the precision of the model. Modeling without the consideration of these features cannot be immediately implemented. Some features are considered by most of the models and are applicable in a general evacuation setting.

A comprehensive survey was carried out to identify and evaluate the existing techniques available in literature (Arulselvan et al. 2008). Recognizing a reasonable level of insufficiencies in multimodal transportation, alternate evacuation routes in case of accidents and congestion, and heuristic exploration of difficult optimization problems, this survey helped explain the deficiencies in current techniques and also identified the key features that significantly affect evacuation efficiency.

As part of a prior CMS initiative, Dr. Pardalos addressed some of these features in evacuation modeling. In the previously mentioned survey, models were classified as analytical or simulation-based and the pros and cons of individual techniques were discussed. The simulation-based models are often employed in reality due to their practical benefits and their flexibility to adapt to dynamic factors (Wolshon et al. 2005). The optimization models have the benefit of being accurate but fail to compete with simulation-based models when applied in real time due to their computational complexity in large instances. There is a recent trend of hybrid models mixing analytical and simulation techniques, exploiting their relative advantages, to be reasonably accurate and precise. Based on this form of organization, Dr. Pardalos has developed a branch-and-price enabled integer programming formulation with a parallel computing capability which was then experimentally verified through simulations.

While a variety of evacuation and coastal/atmospheric computational models exist, several challenges arise when it is desired to couple the behavior of these models. Our efforts address information technology challenges that arise in this context with a unique approach using virtualization technologies. The goal is to provide consistent, self-contained execution environments packaged in software "appliances", which facilitate the coupling of models.

Different models, in particular across disciplinary boundaries, are generally developed by different researchers, from different science domains, and programmed using different languages and software packages, so the option of developing coupled models from scratch or integrating at the source code level is often not available due to the associated high software development costs. Instead, our approach facilitates the coupling of models by presenting virtual environments where unmodified model binary programs can be composed. These environments build on modern virtualization technologies that are increasingly available and adopted in systems ranging from desktops to servers to large data centers, with freely available and commercial products from VMware (Player/Server), Citrix (Xen), Microsoft (Hyper-V), among others.

PIs Davis, Sheng and Figueiredo have ongoing collaborative efforts that leverage such virtualization technologies to create self-contained modeling virtual appliances for both education and research uses (Wolinsky et al 2006). These build upon the Grid Appliance system, which has been customized for educational and research goals in the context of coastal end estuarine sciences in the CI-TEAM and SCOOP projects (see http://cseva.coastal.ufl.edu and respective links for these projects for more details).

2. RESEARCH APPROACH

Leveraging the PIs experience developing educational virtual appliances for the study of storm surge and inundation, an appliance focusing on multimodal transportation is developed and deployed. This appliance is based on an enhanced version of the NSF CI-TEAM and SCOOP educational virtual appliances (http://cseva.coastal.ufl.edu) previously developed. The MTEVA leveraged a prior CMS study (Multimodal Solutions for Large Scale Evacuations: 2008-005) to couple advanced congestion models for multimodal evacuation models with a robust storm surge and inundation model.

Virtual appliances use virtual machines to encapsulate all necessary operating system, models, numerical libraries, GUIs, pre-/post-processing and advanced cyberinfrastructure (CI) tools. These machines then automatically securely access a world-wide "Grid" computing network to provide substantial computational resources for use in the interactive multimodal evacuation scenarios. To interface with the coupled modeling system, an interactive geo-referenced GUI i deployed based on the SCOOP appliance OpenLayers interface. This GUI allows users to select from different domains, storm characteristics, numbers of cars, analytic techniques for computation of the most efficient routes, etc.

Once simulation parameters are selected, a simulation is performed. First, the atmospheric and storm surge models simulate the wind and flooding potential. Next, the transportation network is reconfigured dynamically to account for high waves (closed ports), high winds (closed bridges) or flooding (closed roads). Finally, the most efficient routes are determined and displayed in the OpenLayers interface. After deployment of the coupled system, education content was prototyped to target specific examples. The long term impact of the proposed research is that the study of non-recurrent congestion during extreme coastal storms is better understood. In addition, a tool (the MTEVA) is developed and made available which can be used to facilitate interdisciplinary collaboration and to educate and deliver content for other multimodal solutions to congestion mitigation or transportation engineering in general.

From an analytical perspective of the transportation model, the branch-and-price integer programming formulation developed by the Dr. Pardalos is used to establish optimal routes of evacuation within the appliance. An initial optimal solution is established by the optimization model that incorporates multimodal transportation in its routes. The model later receives its input from the CH3D-SSMS storm surge and inundation model that provides the input to the model in terms of the failed links and nodes in the network (closed bridges and closed ports). The new set of optimal routes for this reconfigured network is then determined without solving the optimization model from scratch. Heuristic and exact strategies are developed to determine the alternate routes of evacuation. The heuristic explorations are based on re-calculating the shortest paths between pairs of origin and destination with link failures.

This solution procedure does not involve the entire optimization model for the new network but rather uses heuristic algorithms to recalculate only those paths that have failed links and nodes and hence provide a computationally effective strategy. The results from the heuristic are compared with the solution of the optimization model solved for the reconfigured network. Then, an empirical guarantee to the approximation of the solution is provided and theoretical guarantees to the solutions are provided. Exact techniques to establish these alternate routes without solving the optimization model entirely are developed using a mathematical formulation. The computation performance of these methods is then be compared and presented.

In the first stage of MTEVA development, with the assistance of Dr. Figueiredo's ACIS Laboratory, a baseline grid appliance is configured and deployed and project partners trained in its use and operation. In the second stage, the interfaces necessary to couple the storm surge and evacuation models are developed. In addition, the hypothetical study domains are constructed and a prototype of the input graphical user interface (GUI) is designed using model interchange formats. In the third stage the models are coupled and an output GUI was developed using OpenLayers. Finally, in the fourth stage, the models and GUIs are transferred to the grid appliance and educational content is developed. An example of a similar educational virtual appliance GUI is shown in Figure 1.
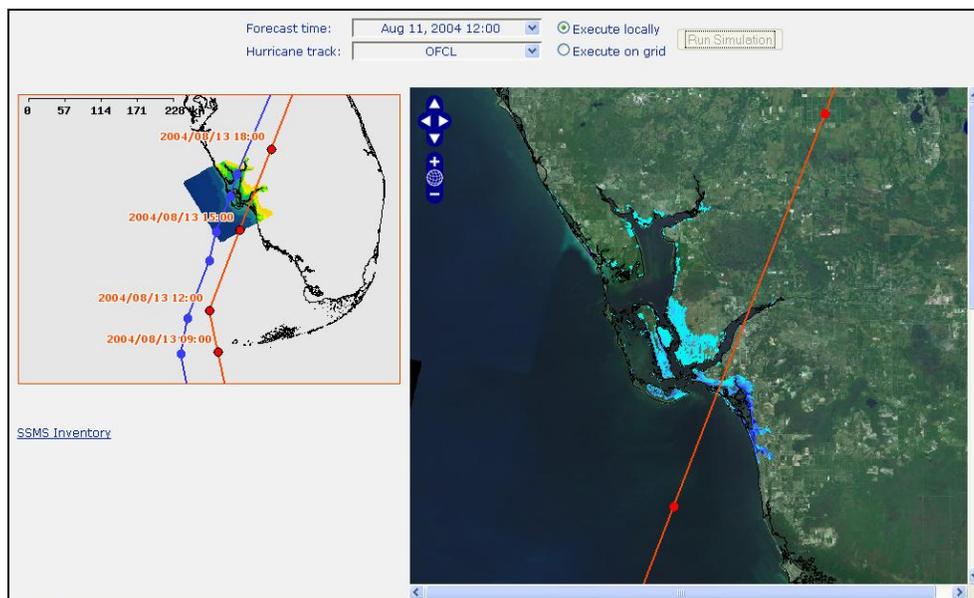
Figure 1 One of the web interfaces used in the SCOOP educational virtual appliance. This interface is used to demonstrate the "forecasting" of inundation during the passage of Hurricane Charley (2004) using different wind fields.

OVERVIEW OF A GRID APPLIANCE

A Grid Appliance (GA) is a self-configuring Virtual Machine (VM) that is used to create and deploy ad-hoc pools of computational resources (Wolinsky et al. 2006). A main motivation of the GA is to provide users who are not experts in information technology and cyber-infrastructure with a plug-and-play computational appliance that makes it possible for end-users themselves to deploy a computational appliance tailored to their own domain of interest. It accomplishes this by combining three key technologies: virtualization of machines and networks, zero-configuration based on peer-to-peer techniques, and job schedulers.

A VM can be thought of as providing a software instance of a physical resource. A VM runs within a Virtual Machine Monitor (VMM) (also called a hypervisor) which either runs within a host computer operating system (e.g. VMware Player) or directly on the "bare-metal" of a physical resource (e.g. VMware ESX). Although multiple VMs can be running simultaneously on a resource, VM's are completely isolated from other running applications, thus providing numerous security, development, and software bundling benefits. Within a GA's VM are all of the necessary operating system, modeling/visualization tools, self-configuration scripts, and cyberinfrastructure middleware for job scheduling and management, to provide the user with a complete end-to-end application.

The GA runs the Debian-based Ubuntu GNU/Linux operating system and includes a lightweight window manager (IceWM) for the X Window System. This interface is accessed through a console connection from the host running the VM (Figure 2-upper left). However, other mechanisms are available to access the appliance including SSH/SCP/SFTP for terminal connections and Samba for file sharing. Additionally, as was used in prior coastal and estuarine science applications, a web server (e.g. the Apache HTTP Server) can be installed to provide web-based access either through the console or through the host computer. Web-based Graphical User Interfaces (GUIs) can then be built to provide very rich and interactive user environments (Figure 2-upper right and lower left/right).

Appliances can run applications locally within the appliance itself or connect to other resources within either a local area network (LAN) or a wide area network (WAN). To date, a majority of appliance applications have focused on executing high-throughput, long-running jobs; however, appliances have also proven successful in performing real-time, forecasting simulations (Davis et al. 2010b). Appliances connect to other resources and form pools using a self-configuring peer-to-peer (P2P) virtual network using private IP addresses called IPOP (Ganguly et al. 2006). Upon starting an appliance, it is automatically connected to a pool of resources and is capable of submitting and executing jobs using a "Grid" scheduler (e.g. Condor, Globus GRAM, PBS, etc.).

Currently, a public infrastructure for bootstrapping such pools is running on PlanetLab (http://www.planet-lab.org); deployments on private resource pools are also supported. For example, pools are currently in place for researchers working on a U. S. National Oceanographic and Atmospheric Administration (NOAA) Integrated Ocean Observing System (IOOS) funded surge and inundation Testbed (http://ioos.coastal.ufl.edu) as well as for the Southeastern Universities Research Association's (SURA's) Coastal Ocean Observing and Prediction Program (SCOOP) (http://scoop.sura.org). The GA approach is fully compatible with cloud-provided "Infrastructure-as-a-Service" (IaaS) resources such as Amazon EC2 as well as national cyber-infrastructures for research and education such as the Science Clouds (http://www.scienceclouds.org) and the NSF FutureGrid (http://www.futuregrid.org). This is an advantage of virtual appliance packaging and the use of virtual networks, that is, a user can run an appliance on local resources, on cloud-provided resources, or both. Amazon EC2 provides an infrastructure where to run appliances, what the Grid Appliance provides in this context is an environment that is tailored to the science community, in particular educators.

To build an "educational" virtual appliance (EVA) like the MTEVA discussed herein, additional domain specific technologies are added to the base distribution of the GA. These technologies can include numerical models (executable or source), statistical analysis packages, data processing scripts, etc. which are then paired with educational lesson plans. This approach allows educators to develop educational content which can be delivered in a very low-level, hands-on environment. However, additional visualization tools can also be incorporated to facilitate the development of high-level, GUI-driven applications which may be more appropriate for some classes of students. The appliance is then used to educate scientists, engineers and students on three key aspects of such environments: application development and deployment on science gateways (for model developers); user, resource and application management (for CI technical personnel); and simulation-based experimentation on science gateways (for end users in research and education). Further details on prior coastal and estuarine science applications of the GA can be found in Davis et al. (2010a, 2010c).
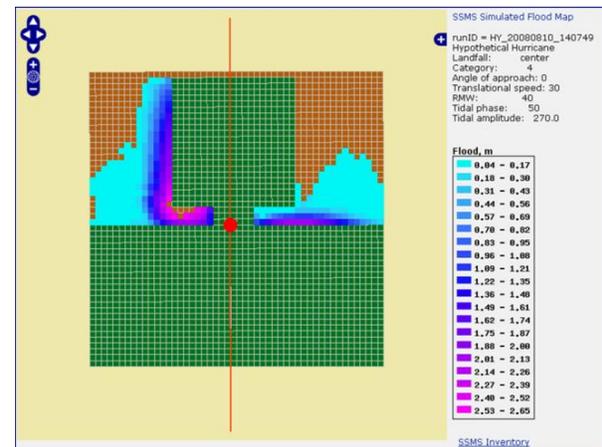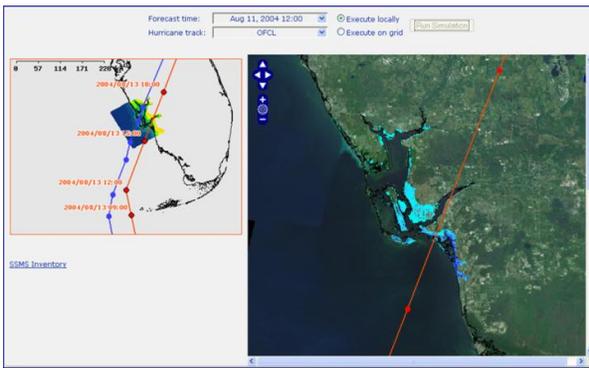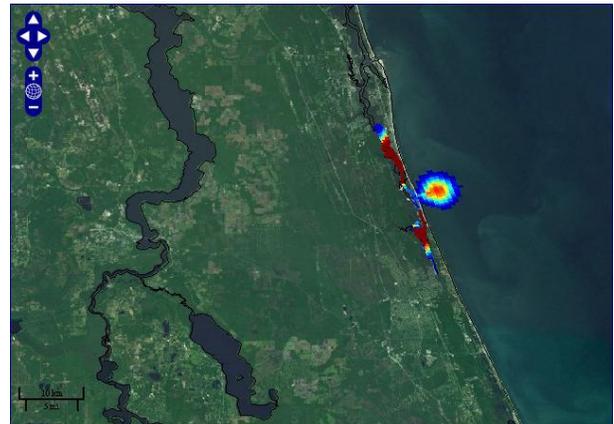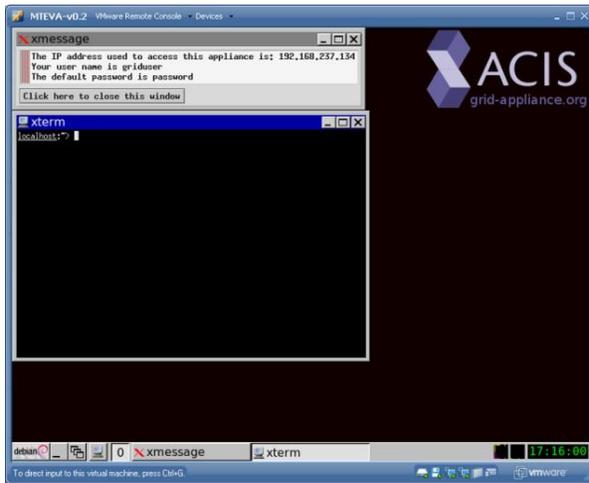
Figure 2 The basic Grid Appliance interface is provided through a simple X-Windows interface (upper left). Prior applications of the Grid Appliance for study of coastal and estuarine science include: a study of a tracer release in the Guana-Tolomato-Matanzas National Estuarine Research Reserve in Northeastern Florida; Charlotte Harbor, Florida's response to Hurricane Charley (2004); and the response of a hypothetical domain to a variety of hypothetical storms.

MODEL COUPLING

The core of the MTEVA is a coupled storm surge and transportation network modeling system. This system, the optimization engine, and all of the associated pre- and post-processing utilities are then packaged into the MTEVA. The main driver of the coupled modeling system is the storm surge model. As this model is simulating the storm surge and inundation response of a storm, it periodically (e.g. once every 15 min) outputs the current pattern of storm surge and inundation as well as the state (all roads passable, certain roads flooded, etc.) of the transportation network. The transportation network optimization model then reads in the state of the network along with a set of capacities, demands etc. and determines the optimal traffic flow. Further details on each of the individual components of this system follow below.

7

STORM SURGE AND INUNDATION MODEL

The simulation of storm surge and inundation is performed using the CH3D-SSMS (http://ch3d-ssms.coastal.ufl.edu) modeling system (e.g. Sheng et al. 2010). The modeling system includes a high resolution coastal surge model CH3D which is coupled to a coastal wave model SWAN and large scale surge and wave models. Currently, CH3D and SWAN can receive open boundary condition from a number of large scale surge models (ADCIRC, UnCH3D, etc.) and wave models (e.g., WaveWatch-III and SWAN, etc.). Finally, a hypothetical analytic storm (Holland 1980) model is also incorporated into the system which, due to high winds and the inverse barometric effect, is the forcing mechanisms which leads to flooding of various parts of the domain.

CH3D-SSMS is validated using many recent Atlantic Basin hurricanes (e.g. Sheng et. al. 2010) and is used to produce a FIRM (Flood Insurance Rate Map) for Pinellas County, FL. CH3D-SSMS was also used to produce surge atlas which was compared with the SLOSH (the model used by the National Hurricane Center) surge atlas. Since 2004, CH3D-SSMS has been advanced to provide real-time forecast of hurricane wind, storm surge, wave, and coastal inundation for various parts of FL and Gulf coasts during hurricane seasons (Sheng et al. 2006; Sheng et al. 2010; Davis et al. 2010b).

The foundation of CH3D-SSMS is the CH3D (Curvilinear-grid Hydrodynamics in 3D) model developed by Sheng (1997, 1990). CH3D has been extensively applied to and validated with data from various coastal, estuarine, and lake waters throughout the U. S. For example, CH3D is the cornerstone of the Chesapeake Bay Model used by the U. S. Environmental Protection Agency and surrounding states to manage water quality and resources. For simulation of storm surge and coastal inundation, CH3D has been enhanced to include flooding-and-drying, current-wave interaction (current-wave bottom boundary layer, wave-breaking induced radiation stress, and wave drag), variable bottom roughness which depends on the variable land use types, and the ability to accept various realistic or analytic wind fields.

NETWORK OPTIMIZATION ALGORITHMS

Scenario Based Instantaneous Evacuation Planning (1st Generation Model)

A model to simulate the instantaneous evacuation planning given a specific scenario is developed in which both a transportation network and demands from all existing nodes are defined. This model minimizes the costs incurred by reversing arcs to evacuate people from all nodes if/when necessary. The solution will show which arcs have to be reversed and how many people should be evacuated through all the arcs. The formulation is shown as follows,

$$\text{Min} \quad \sum_{(i,j)\in A} c_{ij}\beta_{ij}$$

$$\text{s.t.} \quad \sum_{j\in A_i^+} f_{ij} - \sum_{j\in A_i^-} f_{ji} \geq d_i, \qquad \forall i \in N$$

$$0 \leq f_{ij} + u_{ij}\beta_{ij} \leq u_{ij}, \qquad \forall (i,j) \in A$$

$$-u_{ij} \leq f_{ij} \leq u_{ij}, \qquad \forall (i,j) \in A$$

$$\beta_{ij} \in \{0,1\} \qquad\qquad\qquad\qquad \forall (i,j) \in A$$

where c_{ij} is the cost of reversing arc (i,j), d_i is the demand of node i, and u_{ij} is the capacity of arc (i,j). This is a mixed integer linear program, which includes both binary variables, β_{ij}'s, and continuous variables, f_{ij}'s, which are the flows of the arcs.

$$\beta_{ij} = \begin{cases} 1, & Arc\ (i,j)\ is\ reversed; \\ 0, & o/w. \end{cases}$$

This problem is an NP-hard problem (a variant of the knapsack problem); however, it only has $|A|$ integer variables and can be easily solved using integer programming software.

Enhanced Instantaneous Evacuation Planning (Enhanced 1st Generation Model)

The original evacuation model did not include costs associated with travel on any of the arcs. As a result, "cycles" could form in which evacuees would repeat the same closed pathway over and over, an unrealistic result. To alleviate this issue and to make a more robust model, each arc was assigned a travel cost and then the optimization function was modified to minimize this value. The formulation of this new model can be written as:

$$\text{Minimize:} \quad \sum_{(i,j) \in A} c_{ij}\beta_{ij} + \sum_{(i,j) \in A} h_{ij}|f_{ij}|$$

$$\text{Subject to:} \quad \sum_{j \in A_i^+} f_{ij} - \sum_{j \in A_i^-} f_{ji} \geq d_i, \qquad\qquad \forall i \in N,$$

$$0 \leq f_{ij} + u_{ij}\beta_{ij} \leq u_{ij}, \qquad\qquad \forall (i,j) \in A,$$

$$-u_{ij} \leq f_{ij} \leq u_{ij}, \qquad\qquad \forall (i,j) \in A,$$

$$\beta_{ij} \in \{0,1\}, \qquad\qquad \forall (i,j) \in A,$$

where N is the set of all nodes, A is the set of all arcs, f_{ij} is the flow through arc (i,j), c_{ij} is the cost of reversing arc (i,j), d_i is the demand of node i, u_{ij} is the capacity of arc (i,j), h_{ij} is the travel cost of arc (i,j), and the binary variable β_{ij}, is defined as

$$\beta_{ij} = \begin{cases} 1, & \text{if arc } (i,j) \text{ is reversed;} \\ 0, & \text{otherwise.} \end{cases}$$

This new model was tested and incorporated into the MTEVA.

Dynamic Traffic Assignment Model for Evacuation Scheduling (2nd Generation Model)

Compared to the instantaneous model, a more comprehensive and realistic model should include the temporal information of all these arc reversals and flows. To be able to do this, a time expanded network model would be more appropriate, where all the arcs are given another index, time point.

When the temporal indices are added to all variables, it also greatly increases the computational costs, because it not only increases the number of integer variables to $O\left(|A| \times \frac{T(T-1)}{2}\right)$, but also introduces more constraints, such as travel time upper bound and lower bound constraints, first in first out constraints, unique realization constraints and so on. The next step builds a more realistic and comprehensive evacuation scheduling model on a time expanded network, which will help determine when to reverse an arc and what amount of people should be sent at a specific time point before the node is destroyed by hurricanes or even tsunamis. Because of computational intensity of this model, developed a new decomposition algorithm has been developed to solve it both effectively and efficiently.

In the time expanded network, copies of each node are made first by adding time stamp to define the time expanded nodes. And then the time expanded nodes are connected to form time expanded arc, each of which has a tail node with smaller time stamp and head node with a bigger time stamp. The following is an example of a time expanded arc.
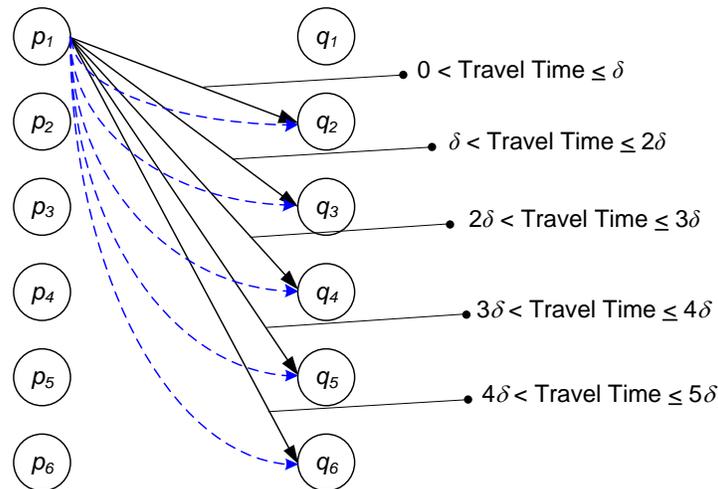
In the above graph, the binary variable $z_{p_t, q_{t+\tau}}$ is used to denote whether time expanded arc $(p_t, q_{t+\tau})$ is realized, because in reality there is only one unique travel time for anybody. The constraints are

$$\sum_{\tau \in \Delta_{p,q}} z_{p_t, q_{t+\tau}} = 1,$$

$$y_{p_t, q_{t+\tau}} \leq M_{p,q} z_{p_t, q_{t+\tau}}$$

where $y_{p_t,q_{t+\tau}}$ denotes the follow on the time expanded arc. In order to determine the travel time of an arc, the following constraint is included,

$$\sum_{\tau \in \left(\Delta_{p,q} \setminus \delta\right)} (\tau - \delta) z_{p_t,q_{t+\tau}} \leq \phi_{p,q}\left(x_{p,q}(t)\right) \leq \sum_{\tau \in \left(\Delta_{p,q}\right)} \tau z_{p_t,q_{t+\tau}}, \quad \forall (p,q) \in A, t \in T$$

where $x_{p,q}(t)$ is the number of vehicles on arc (p,q) at time t.

In order to model arc reversal another variable $\beta_{p,q}^t$ is introduced to denote if the arc (p,q) is reversed at time t and use $z'_{p_t,q_{t+\tau}}$ to denote the realization of the reversal arcs,

$$\sum_{\tau \in \Delta} z_{p_t,q_{t+\tau}} \leq \beta_{p,q}^t$$

$$\sum_{\tau \in \Delta} z'_{p_{t+\tau},q_t} \leq (1 - \beta_{p,q}^t)$$

However, the following tighter formulation can be used without using $\beta_{p,q}^t$

$$\sum_{\tau \in \Delta} z_{p_t,q_{t+\tau}} + \sum_{\tau \in \Delta} z'_{p_{t+\tau},q_t} \leq 1, \forall (p,q) \in A, t \in T$$

If an node (p) is not valid (destroyed by hurricane at time t), then
1) Arrival at the node must occur earlier than t

$$z_{q_{\tau-\eta},p_\tau} = 0, \quad \forall q, \eta, \tau \geq t$$
$$z'_{p_\tau,q_{\tau-\eta}} = 0, \quad \forall q, \eta, \tau \geq t$$

2) The node must be left by t

$$z_{p_\tau,q_{\tau+\eta}} = 0, \quad \forall q, \eta, \tau \geq t$$
$$z'_{q_{\tau+\eta},p_\tau} = 0, \quad \forall q, \eta, \tau \geq t$$

Actually this means that all these arcs can be dropped in the time expanded network. Upon the above definitions and formulations, the DTA-Evacuation model can formulated as follows,

$$\text{Min} \quad \sum_{(p,q)\in A}\sum_{t\in T}\sum_{\tau\in\Delta}\tau(f_{p_t,q_{t+\tau}} + f'_{p_t,q_{t+\tau}})$$

s.t.   Flow balance constraints,

Travel time constraints,

$$\sum_{\tau\in\Delta}z_{p_t,q_{t+\tau}} + \sum_{\tau\in\Delta}z'_{p_t,q_{t+\tau}} \leq 1, \forall(p,q),t$$

$$z_{p_t,q_{t+\tau}} + \sum_{\eta\in\Delta}z'_{p_{t+\zeta},q_{t+\eta}} \leq 1, \quad \forall\delta\leq\zeta\leq\tau-\delta$$

$$z, z' \in \{0,1\}^N$$

The following is a demonstrative example of the DTA-evacuation model to show its efficacy,

1) The following graphs show the water level Water level of +1 and +3 hour (planning horizon 1-2).

The following shows the scheduling of the above time points,
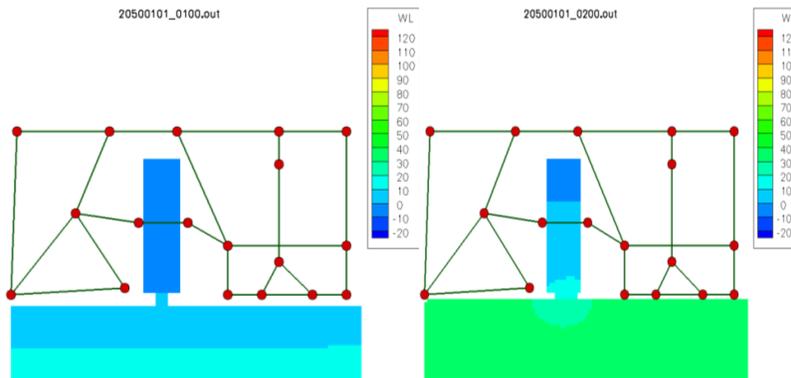
Planning Horizon 1 - 2
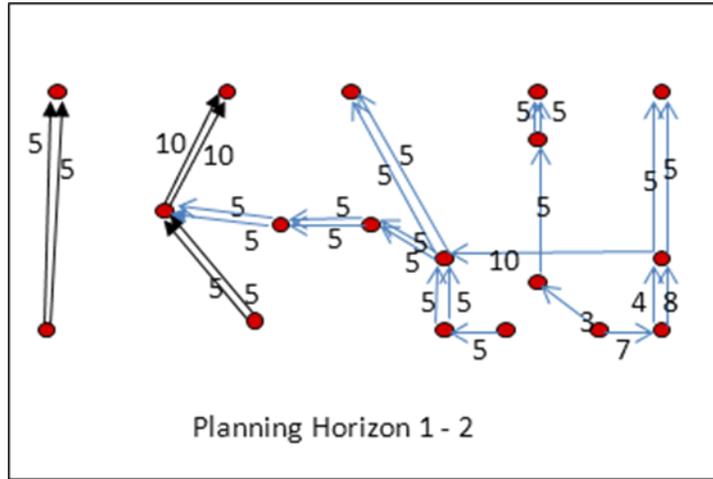
2) The following graphs show the water level Water level of +6 and +9 hour (planning horizon 3-4).

The following shows the scheduling of the above time points,

Planning Horizon 3 - 4

13
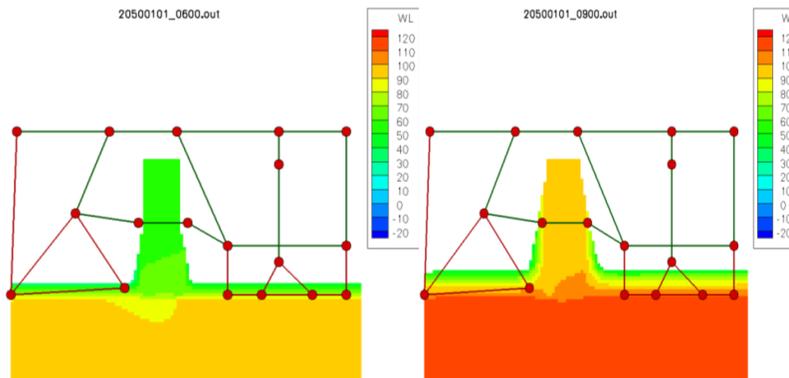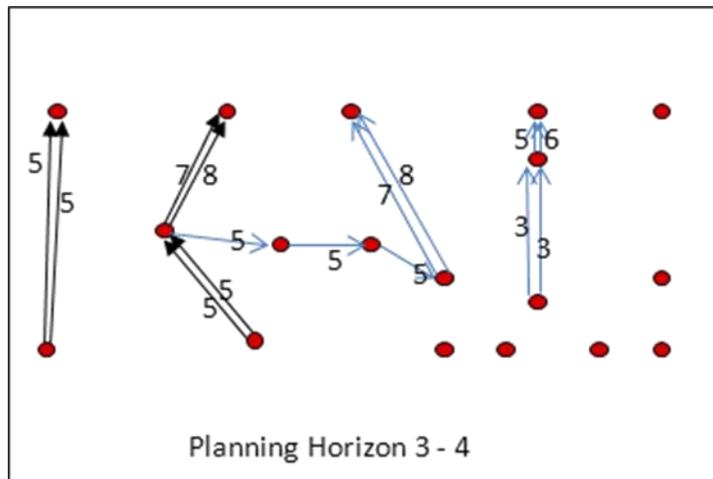
Heuristic Approach to Solution

In order for scalability to be ensured, a heuristic approach is designed and implemented. It was also tested in a series of large-scale randomly generated instances to validate it.

First, it is a known issue that in a real-life evacuation scheme, the original exact methodology proposed is highly inefficient and computationally expensive. It becomes imperative then to adopt a heuristic approach. When dealing with heuristic methods, the tradeoff between computational cost and solution quality must be analyzed.

In general, the algorithm for a dynamic traffic assignment/evacuation planning system is:
1. Read the node/arc status and the demands
2. Solve the network flow problem at each iteration
3. Update the demands
4. If there are still vehicles using the network, proceed to 1. Otherwise, terminate.

Clearly there are a couple of issues with the approach:
- How can the exact position of a vehicle be known after it has left a node?
- How can it be ensured that a vehicle is not routed towards an arc that has been destroyed?

The above questions, among others, have made the testing process of the algorithm a necessity. An Augmented Lagrange approach is being implemented to solve the issues encountered in a large-scale, dynamic framework. Preliminary results are presented below:

Table 1. Efficiency estimates of the Augmented Lagrange approach

Network Size (nodes)	Average Optimality Gap (%)	Maximum Optimality Gap (%)	Average Time Decrease (%)	Maximum Time Decrease (%)
16	0.21	1.05	90	91.5
100	0.26	0.98	94	95
1000	0.33	1.05	95	97
Overall	0.3	1.7	92	97

In the future, sparsity factors will be investigated along with the application of the algorithmic framework of Lagrange Duality in a real-life large-scale evacuation management suite.

ALGORITM IMPLEMENTATION

The original versions of the models used CPLEX, however, CPLEX is proprietary software and will make for more complicated inclusion into the virtual appliance due to licensing restrictions. Hence, the public domain optimization software GLPK (GNU Linear Programming Kit) (http://www.gnu.org/software/glpk) is now being used.

SURGE-TRANSPORTATION COUPLING

The evacuation planning and storm surge modeling system are coupled through the exchange of node-arc information between the two models. Initially, the storm surge model is provided with locations of the nodes and arcs. As a storm approaches and makes landfall, the storm surge models checks to see if the arcs become impassable (e.g. due to flooding or excessive wind speed on a bridge) and if so, the storm surge model informs the evacuation model and the evacuation plan is updated.

During a simulation, potential nodes fall into several possible categories: 1) The node is connected to one or more other nodes via an arc; 2) The node is isolated and no longer has any connections (e.g. due to a flooded road), but may reconnect in the future; or 3) The node has been destroyed and will never again be connected to any other nodes. Nodes are considered destroyed if flooding exceeds some critical value, H_{Ncr}.

Each arc within the network is defined as either a "road" or a "bridge". A road is considered indestructible, while a bridge is not. Roads are assumed at some height, R_A, above (or below) the surrounding topography and become unusable if, during the course of a simulation, the water level at any location on the road exceeds some critical value, H_{Acr}, above the road. If, at any point of time later, the water level retreats – the road becomes usable again. Each bridge has its own elevation relative to the simulation vertical datum (e.g. NAVD88), B_A. If, during the course of a simulation, the water reaches the bridge, it's then considered "destroyed" and permanently unusable. Additionally, regardless of water level, bridges are also assumed to be impassable during periods of high wind when the wind speed exceeds some critical value, W_{Acr}. Finally, for simplicity, optimization costs for the current application were set to constant values, each value of c_{ij} was set 1 and each value of h_{ij} was set to 0.1.

OVERVIEW OF THE NETWORK OPTIMIZATION INPUT AND OUTPUT FILES

During operation of the coupled modeling system, multiple input and output files are used (Table 2). While a few of these files remain constant in time, a majority are time varying. Thus, these filenames contain the simulation time of the time they represent. In addition to the normal input (e.g. fort.4) and output (e.g. fort.24) files used in the operation of the storm surge model, a new input file has been created (ch3d_road_network.in). Present within this file are the numbers of nodes, the numbers of arcs, the spatial locations of all the nodes of the transportation network and the initial connectivity matrix. This matrix also distinguishes between arcs defined as 1) roads or 2) bridges.

Table 2   A description of the input and output files used in the coupled modeling system. "YYYYMMDD_HHMM" refers to the simulation time that the data file represents.   For example, flow_20100801_2359.txt would represent the connectivity matrix for the simulated time of 11:59pm on Aug. 1, 2010. Astronomical times are used and referenced to the time zone of the storm surge model which is generally UTC.

Model	File Type	Filename	Description
Storm Surge (S.S.)	Input from user	fort.4, fort.15, fort.32, … ch3d_road_network.in	S. S. Input files Network description
	Output to plot	fort.24, fort.25, fort.28, …	S. S. Output files
Exchange Files	Output from S. S. / Input to N. O.	node_status_YYYYMMDD_HHMM.txt flow_YYYYMMDD_HHMM.txt	Node status Connectivity matrix
Network Optimization (N.O.)	Input from user	capacity.txt demand.txt safety.txt	Network capacity Network demand List of safety nodes
	Output to plot	result_YYYYMMDD_HHMM.txt safety_YYYYMMDD_HHMM.txt feasibility_YYYYMMDD_HHMM.txt	Resulting network use Result at safety nodes Feasibility of solution

Output from the storm surge model includes a file describing the current status of each node (node_status_*.txt) (defined previously as "1", "2", or "3") as well as an updated connectivity matrix (flow_*.txt). For the network optimization model, three files are used as input. The first two files (capacity.txt and demand.txt) define the capacity and demand of the network. The third file (safety.txt) defines a list of safety nodes. These nodes represent the destinations (e.g. inland cities, hotels, shelters, etc.) of traffic within the network. The main output files of the network model include the resulting traffic on each arc (result_*.txt) and the result at each of the safety nodes (safety_*.txt). Under certain conditions, the optimization problem may be infeasible (e.g. too much demand for too little network capacity). Thus, an additional file is created which contains the feasibility of the GLPK solution as defined by the Karush-Kuhn-Tucker integer feasibility conditions (KKT.PE and KKT.PB).

DESIGN OF THE MTEVA

Starting from the base GA distribution VM, several software components are added to build the MTEVA. To begin, an executable version of the CH3D-SSMS modeling system specifically configured for the hypothetical domain was added. Then, the publically available GLPK optimization engine was added as well as the network optimization model. This model consists of a simple program which reads the configuration of the network and converts this information into CPLEX LP format, an algebraic formulation solvable by GLPK. To facilitate enhancement of the model by future users, both source and executable are included. Then, several pre- and post-processing scripts were added to aid in data exchange and plotting. Finally, the Apache HTTP Server was added to the appliance and a simple web interface developed to interface with the modeling system. With these components added, several web pages were designed to provide input (JavaScript) and output (OpenLayers) GUIs along with some simple simulations management pages to allow access to previously performed simulations available within the local simulation database in a manner similar to approach described in Davis et al. (2010c).
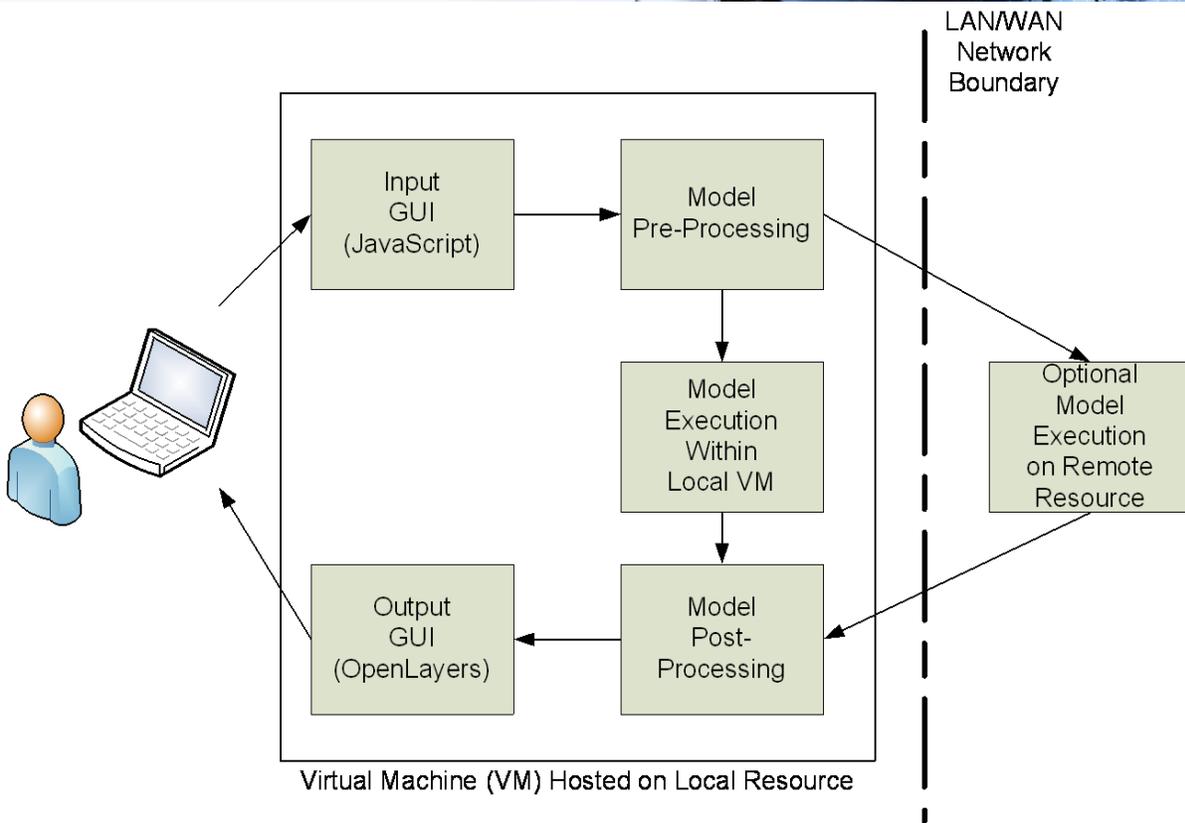
Figure 3 Overview of the MTEVA design.

3. FINDINGS AND APPLICATIONS

EVACUATION SCHEDULING RESULTS

In order to test the evacuation scheduling algorithms, a simple study domain is constructed. This domain consists of a simple coastline, with a narrow inlet and large bay. A simple transportation network is overlaid which contains 18 nodes and various interconnecting arcs. Additionally, a hypothetical set of capacities and demands is created to test the evacuation model. Further descriptions of the study domain are found in Appendix B. Finally, a hypothetical storm is created which floods/dries various parts of the domain and transportation network (Figure 4).

| + 9 hr | +12 hr |
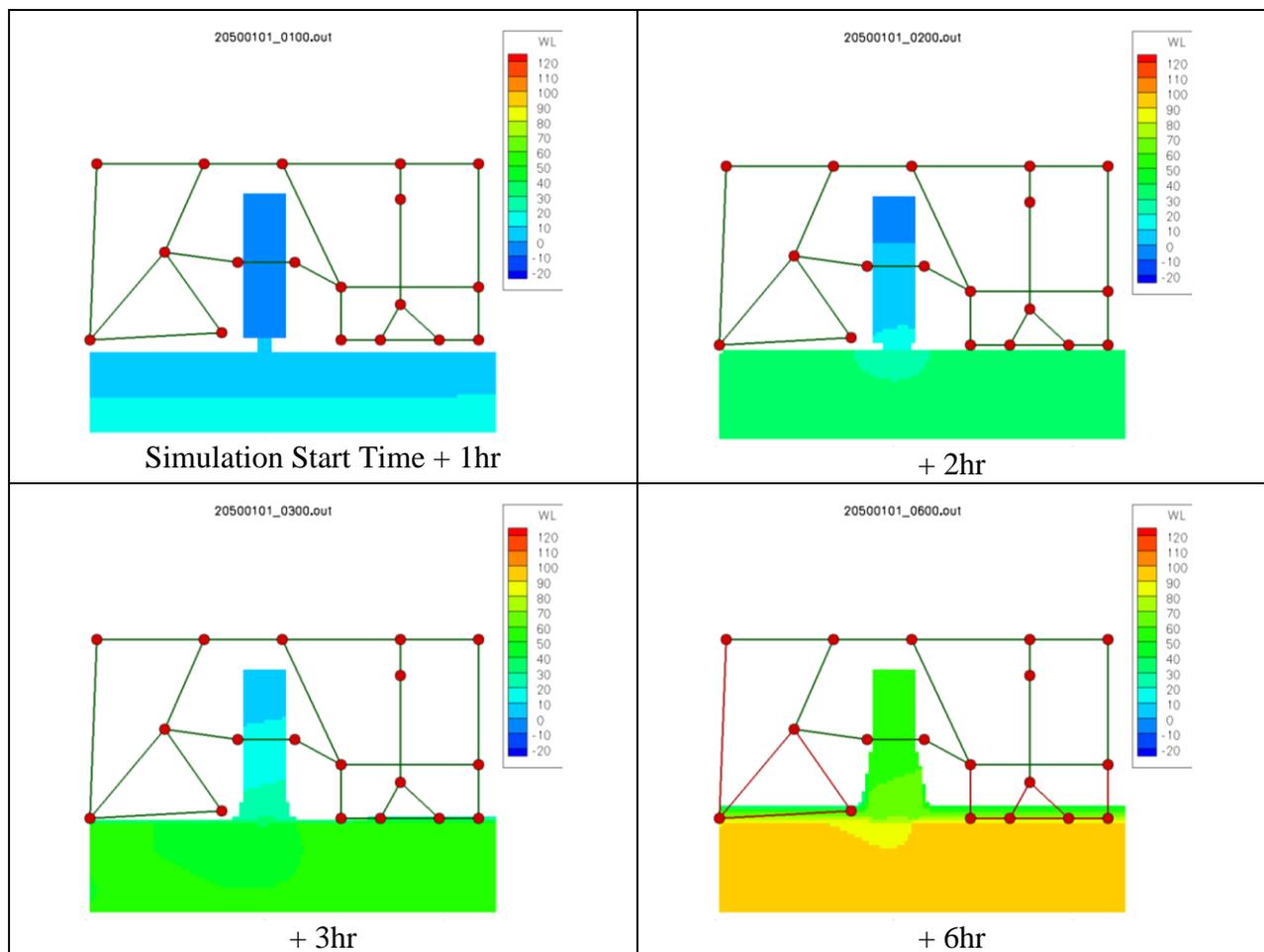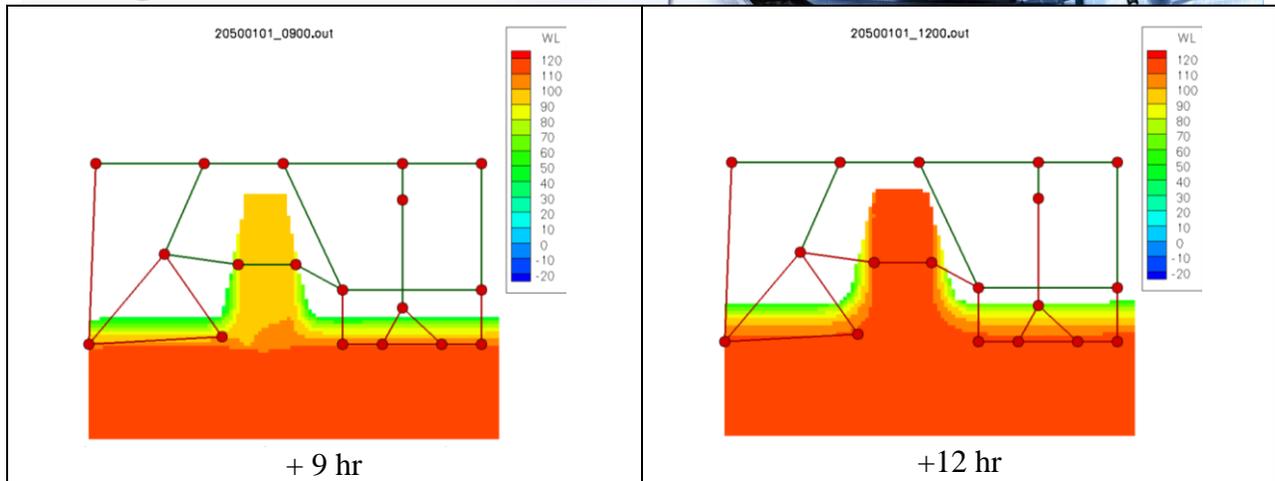
Figure 4 Inundation of the transportation network during landfall of a hypothetical storm. As network links become unusable (e.g. due to coastal inundation or high wind speeds on bridges) the link colors change from dark green to red. The contours respresent the height of storm surge water level (WL).

RESULTS

An example of the simulated evacuation plan is shown in Figure 5.
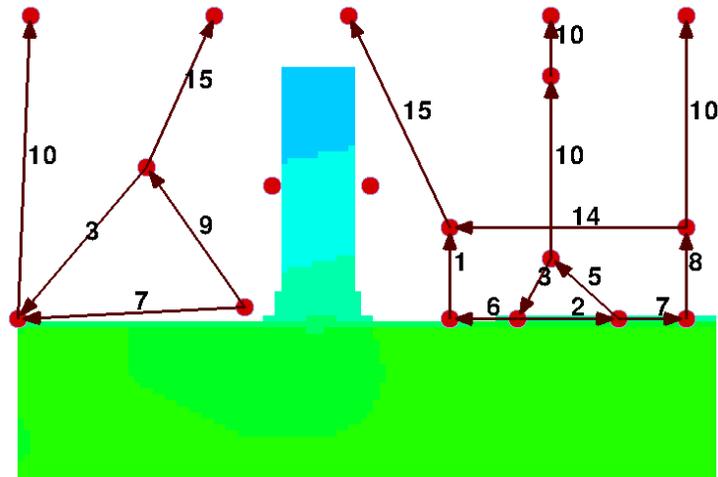
Figure 5 Instantaneous evacuation plan at +3 hr describing the numbers of people to be evacuated.

WEB-BASED GRAPHICAL USER INTERFACE (GUI)

The web-based GUI and is developed using JavaScript, the PHP scripting language (http://www.php.net), and OpenLayers (http://www.openlayers.org). Simulated parameters are made available as a Web Mapping Service (WMS) using MapServer's PHP MapScript and then plotted using OpenLayers. OpenLayers is a JavaScript library for displaying maps in web browsers capable of visualizing any WMS or Web Feature Service (WFS). The interface is accessed by connecting a web browser to the Apache HTTP Server running locally on the Appliance. An example of the interface used to begin a simulation is shown in Figure 6. The web interface allows a user to setup and perform simulations of the coupled modeling system using a simple set of drop-down boxes.
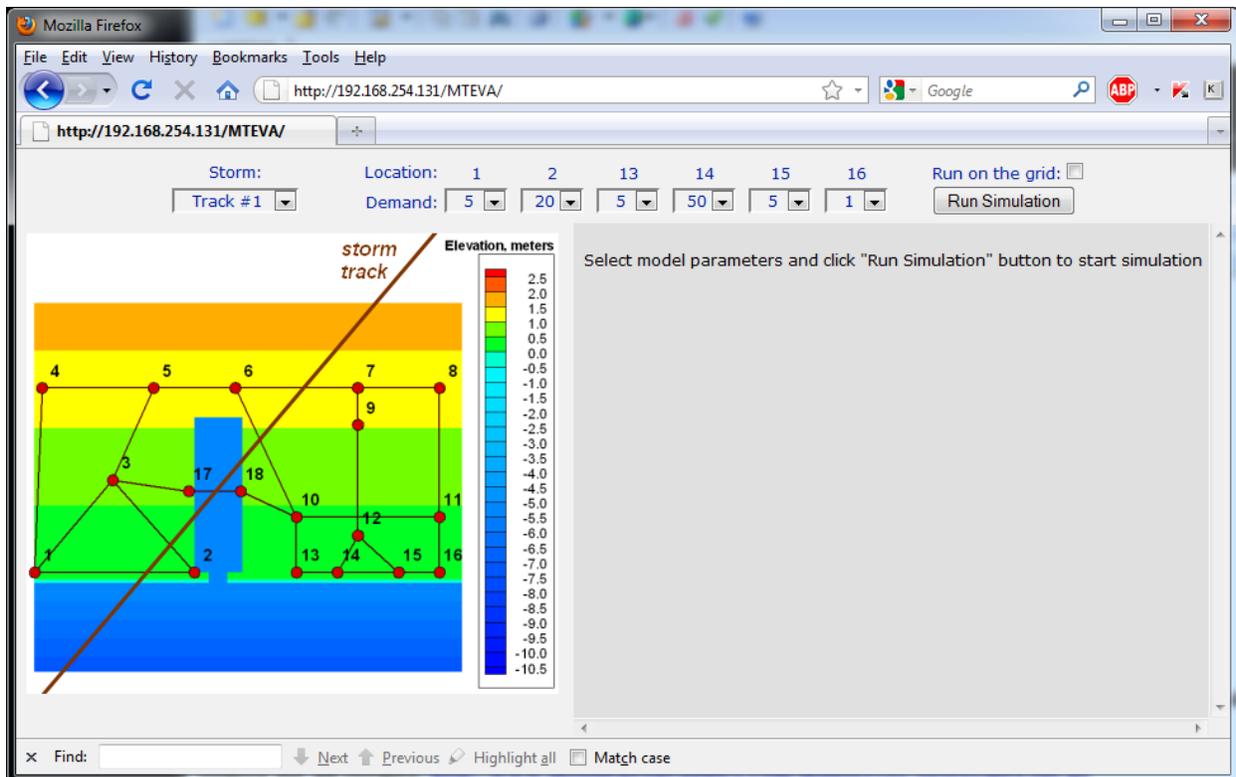
Figure 6 The MTEVA Graphical User Interface (GUI) demonstrating the bathymetry/topography of the system and the JavaScript drop boxes used to select simulation parameters (upper). Default values of network demand (lower left) and capacity (lower right).

Once the simulation parameters are selected and the system configured to run locally or on a remote Grid resource, "Run Simulation" is clicked. Once the simulation is complete, an animation displays the domain being flooded along with the updated evacuation routing (Figure 7).
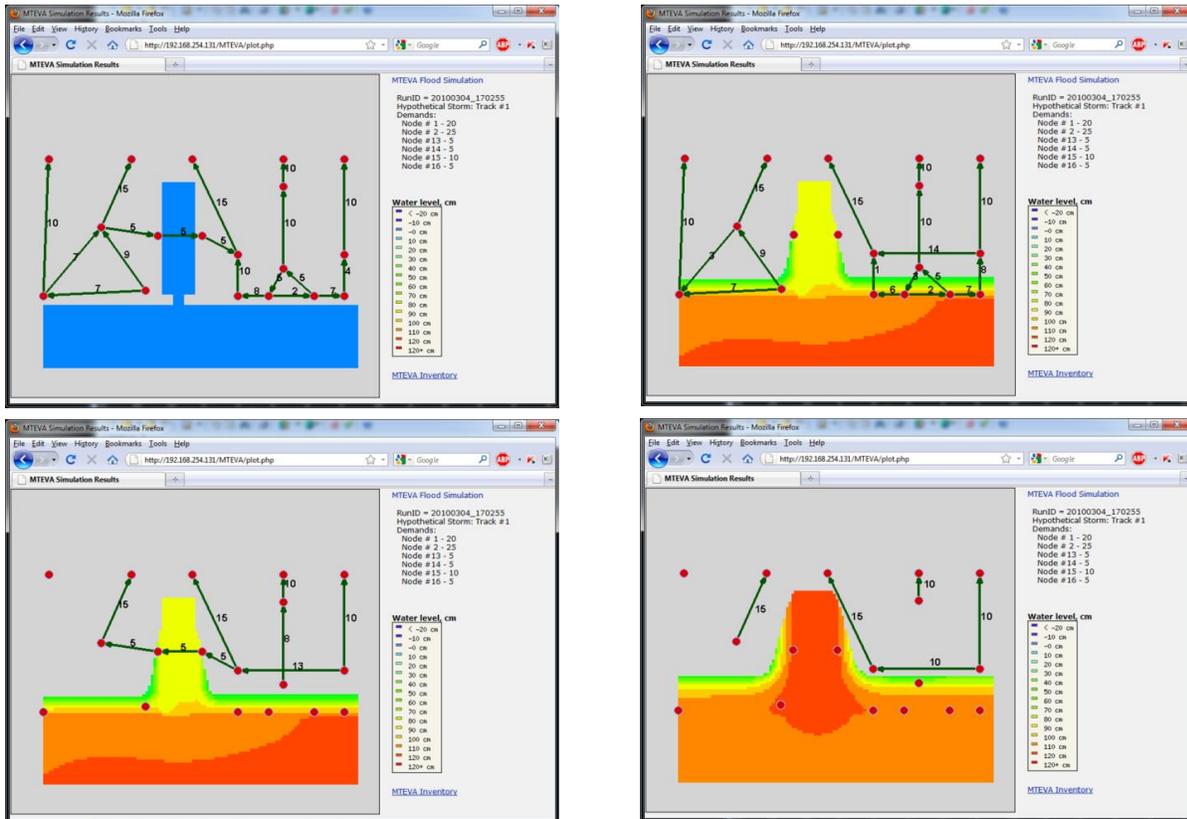
Figure 7 Examples of simulated storm surge / inundation and the coupled transportation networking routing at several time instants showing the gradual progression of storm surge into the domain breaking the arc connections between nodes: T_1 (upper left), T_2 (upper right), T_3 (lower left) and T_4 (lower right).

MTEVA ONLINE CONTENT

The MTEVA is available online at http://cseva.coastal.ufl.edu. Content provided includes background on the individual models (storm surge and optimization) as well as how they are integrated and used within the appliance.

Figure 8 Web content describing the models incorporated into the MTEVA.

Figure 9 Web content describing the design of the MTEVA.

EDUCATION AND OUTREACH ACTIVITIES

Graduate Student Survey

To assess the effectiveness of using the MTEVA for research and education, a preliminary opinion survey was developed and then conducted using graduate students in the College of Engineering at the University of Florida. Seven participants were selected from a pool of candidates derived from the graduate programs involved in the major science concepts of the MTEVA: Coastal and Oceanographic Engineering (Coastal), Transportation Engineering (Trans), and Industrial and Systems Engineering (ISE) (e.g. optimization). None of the participants were directly involved with the development of the MTEVA, none of the participants were supervised by any of the personnel involved in the project, and none of the students had any prior experience with using the MTEVA or any other Grid Appliance. However, participants selected were expected to have some familiarity with computers as they were required to have the ability/capability to install software on their own computers. Each science topic was broken down into five general questions in which the participants were asked to respond: I understand the general concept of [topic]; I am able to visualize the concept of [topic]; I understand the governing physics/mathematics of [topic]; I understand the general concepts of a numerical model of [topic]; and I am familiar with using a numerical model for the simulation of [topic].

As part of the survey, input was collected from participants prior to presenting any information about the MTEVA (Initial understanding) and after participants completed a hands-on assignment where they used the MTEVA on their own (Final understanding). To quantify the initial level of understanding, participants were asked their opinion on several science topics: storm surge and inundation; optimization; and transportation engineering. After which, the participants were then asked to perform a "take home" assignment. As part of this assignment, each participant was to download and install the MTEVA on their own computer and then perform a simple experiment guided by a web-based tutorial. After providing the results of the experiment, participants were then asked their experiences on using the MTEVA and what their "Final understanding of [topic] based on my use of the MTEVA." Throughout the survey process, each participant was tracked using an anonymous identifier to assess individual change in understanding. Finally, in addition to the science topics, participants were asked their understanding of "virtualization" both before and after their assignment. It is also noted that a survey was conducted at the mid-point of the survey after participants were given a short overview presentation of the MTEVA. However, as the final survey was conducted anywhere between several days and a week after this presentation, it was theorized that this presentation did not bias the participants final understanding of the various topics. This theory was verified through follow-up interviews with several participants who confirmed their final survey response was relative to their initial understanding.

Participants were asked to respond all questions using a 9-point Likert Scale. The scale ranged from 1 (strongly disagree) to 9 (strongly agree) with 5 being the mid-point (uncertain). A visual scale was provided with equal spacing indicated between each number (1-9) and showing symmetry between the extremes. Thus, for purposes of the analysis presented herein, the individual Likert items are treated as interval-level data (as opposed to ordinal data as is commonly regarded for smaller scales). Furthermore, all of the scores within a given discipline were aggregated and then normalized by the number of participants from that program to obtain a program average. The three program averages (Coastal, Trans and ISE) were then averaged to obtain an overall average.

The results of the survey are summarized in Table 3-Table 5. In the discussion to follow, the notation (Initial -> Final) is used to refer to the progression of the average scores at the three survey phases. Table 3 indicates that, based on the topic of the questions, the overall level of understanding was enhanced based on the participant use of the MTEVA (4.6 -> 7.0) was improved by 2.4. Excluding the virtualization topic (as most participants had little experience with virtualization - average initial score 3.4) and focusing on the science topics, understanding (4.9 -> 7.1) was improved by 2.2. Significant improvement was shown in understanding of each individual topic area: storm surge (4.0 -> 7.5) by 3.5, optimization (5.7-> 6.8) by 1.8, transportation (5.1 -> 7.2) by 2.1, and virtualization (3.4 -> 6.5) by 3.1. It is noted that there is great familiarity between the ISE and Transportation programs and as such, the improvement in the optimization and transportation topics was not as great as the other topics. Results shown in Table 4 indicate that the MTEVA was most effective enhancing the ability of participants to visualize concepts (5.2->7.8), an improvement of 2.6. Results also indicate that, regardless of the posed question type, the MTEVA increased understanding (average increase of other types was 2.1).

A summary of the MTEVA specific questions asked after completion of the assignment is shown Table 5. This table groups questions into several broad categories: ease-of-use (average score of first four questions is 8.3), enhancement of science understanding (7.0), understanding of what it is designed to do (8.4), suitability for education activities (7.0), and willingness to promote the technology (6.2). Our hypothesis that the MTEVA provides an easy-to-use framework for dissemination of models across different platforms was confirmed by the observation that: MTEVA scored very high in ease-of-use; the participants used different, independently-configured platforms (e.g. their own laptops with MS Windows / Mac OS X operating systems) and that it took less than an hour for most to install and get it up and running. Although participants seemed to agree that it is appropriate for undergraduate / graduate students, they thought the MTEVA would be less appealing for K - 12.

Table 3 Summary of survey results based on science topic.

Question topic	Coastal		ISE		Trans		Average	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Storm Surge	6.0	7.0	2.2	7.4	3.8	8.0	4.0	7.5
Optimization	1.0	4.8	7.6	8.1	8.6	7.4	5.7	6.8
Transportation	1.0	4.8	5.3	8.1	9.0	8.6	5.1	7.2
Virtualization	3.4	6.4	5.6	7.6	1.2	5.6	3.4	6.5
Average	2.9	5.8	5.2	7.8	5.7	7.4	4.6	7.0

Color Ramp		
1	5	9

Table 4 Summary of survey results based on question type.

Question type	Coastal		ISE		Trans.		Average	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
General concept	3.0	6.3	5.9	8.2	8.0	9.0	5.6	7.8
Visualize concept	3.0	6.3	4.6	8.1	8.0	9.0	5.2	7.8
Physics	3.0	6.3	4.9	7.6	7.3	7.7	5.1	7.2
Model concepts	2.7	5.7	5.1	7.7	6.7	7.0	4.8	6.8
Model use	1.7	3.0	4.7	7.7	5.7	7.3	4.0	6.0
Average	2.7	5.5	5.0	7.9	7.1	8.0	4.9	7.1

Color Ramp		
1	5	9

Table 5 Summary of MTEVA-specific survey questions.

Question	Coastal	ISE	Trans.	Average
I found the web documentation on the installation of the MTEVA sufficient.	9.0	6.8	9.0	8.3
I found the MTEVA easy to setup and install.	9.0	6.8	9.0	8.3
I found the documentation on setting up and running different MTEVA scenarios useful.	9.0	7.0	8.0	8.0
I was able to get the MTEVA up and running is less than an hour.	9.0	7.4	9.0	8.5
I believe my understanding of storm surge was enhanced by the use of the MTEVA.	8.0	7.4	9.0	8.1
I believe my understanding of optimization was enhanced by the MTEVA.	8.0	5.2	5.0	6.1
I believe my understanding of traffic network routing was enhanced by the MTEVA.	8.0	5.0	9.0	7.3
I believe my understanding of virtualization was enhanced by the use of the MTEVA.	8.0	4.8	9.0	7.3
I believe my understanding of grid computing was enhanced by the use of the MTEVA.	8.0	5.2	6.0	6.4
Once I used it, I understood the MTEVA better than just seeing the presentation.	9.0	6.4	9.0	8.1
I would like to see the MTEVA applied to a real transportation network/hurricane.	9.0	8.2	9.0	8.7
I believe the MTEVA could be a useful educational tool for graduate students.	9.0	7.0	9.0	8.3
I believe the MTEVA could be a useful educational tool for undergraduates.	9.0	6.2	7.0	7.4
I believe the MTEVA could be a useful educational tool for K-12 students.	5.0	5.8	5.0	5.3
I would like to try other applications of the GA technology for my field.	8.0	5.6	9.0	7.5
I would consider creating a Grid Appliance application for my research.	5.0	4.6	5.0	4.9
I would recommend creating a Grid Appliance application to friends.	7.0	5.0	7.0	6.3
Average	8.1	6.1	7.8	7.3

Color Ramp		
1	5	9

Seminars, Conferences, and Refereed Publications

CMS Student Conference 2010

Two graduate students currently working on the MTEVA project presented at the Center for Multimodal Solutions for Congestion Mitigation Annual Student Conference (Tutak et al. 2010 and Zheng et al. 2010). Qipeng (Phil) Zheng (Industrial and Systems Engineering) discussed the optimization routines developed for the MTEVA in his oral presentation. Bilge Tutak (Civil and Coastal Engineering) discussed the overall MTEVA design and performed a live demonstration during his poster presentation. Students were judged on the quality of their material / presentation and awards were given to the most outstanding work in both the oral and poster presentation categories. Phil and Bilge each won awards in their respective categories.

NWS WeatherFest 2011

The coastal scientists involved in the development of the MTEVA (the PI, Co-PI Davis, a post-doc and several graduate students) presented an overview of their research at the National Weather Service Jacksonville's WeatherFest (Sheng et al. 2011). As part of this effort, development on the MTEVA was highlighted.

CMS Student Conference 2011

To update progress on the MTEVA from the prior year's CMS presentation, Chrysafis Vogiatzis (Industrial and Systems Engineering) gave a presentation on recent enhancements to the MTEVA (Vogiatzis et al. 2011a). Highlighted in the presentation were recent improvements in the optimization algorithms.

ITE Summer 2011 Undergraduate Transportation Seminar

To reach out to undergraduate transportation engineering student, a graduate student in currently working on the development of the MTEVA participated in the University of Florida Institute of Transportation Engineers Undergraduate Transportation Seminar. Chrysafis Vogiatzis (Industrial and Systems Engineering) provided an overview of the MTEVA targeted at a diverse audience of undergraduate and graduate transportation engineering students (Vogiatzis et al. 2011b).

ICEM 2011

The MTEVA will be more formally debuted at the 2nd International Conference on Evacuation Modeling and Management. Included as part of the upcoming presentation and associated journal publication will be a complete overview of the MTEVA as well as results of student surveys on the effectiveness of the application to aid in interdisciplinary education (Davis et al. 2011b).

ECM Conference 2011

Through funding provided by Florida Sea Grant, the MTEVA was integrated with several other formerly independent coastal science applications into a single new appliance: The Coastal Science Educational Virtual Appliance (CSEVA) (http://cseva.coastal.ufl.edu). The applications included span a wide variety of coastal science applications and their integration enhances the user experience (less local storage requirements, easier to install, linked application scenarios, etc.) In addition to the MTEVA developed in this study, the CI-TEAM and SCOOP applications were included. The CI-TEAM application simulates the release of a tracer into the waters of the Indian River Lagoon estuarine system (northeast Florida).   The SCOOP application simulates storm surge and inundation in two different domains: a simple domain being impacted by a hypothetical storm and Charlotte Harbor (southwest Florida) being impacted by various different wind forecasts for Hurricane Charley (2004). The development of the CSEVA will be presented (along with a corresponding refereed publication) at the 12th International Conference on Estuarine and Coastal Modeling to be held later in the year (Davis et al. 2011a).

4. CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

The development of a unique, self-contained, software environment, the MTEVA has been completed. The MTEVA seeks to assist in coastal science, transportation and cyberinfrastructure research, education and outreach by creating a coupled modeling system capable of simulating the transportation network response to a system subject to high winds, storm surge, and inundation. The MTEVA use of VMs, allows individual science components to be brought together in a simple-to-use infrastructure where users can focus on learning the science instead of trying to setup and perform simulations. The MTEVA:

- contains a storm surge and inundation modeling system coupled with a traffic network optimization model capable of simulating lane reversal. The coupled modeling system is then applied to a representative coastal domain and transportation network.

- incorporates both basic and advanced user interfaces. At the most basic level, users can access the MTEVA through the web-based GUI. However, for more advanced users, terminal access can also be used to directly setup and perform simulations using the scheduling interfaces directly (e.g using the "condor_submit" command).

- is completely configurable, customizable and expandable. Because of the tools, scripts, web interfaces, etc. are located within the MTEVA; any individual component can be altered to meet and individual user's need. For example, locations of nodes modified, additional network nodes/arcs can be added, or demands and capacities changed.

- is developed using publicly available technologies. All technologies used in the MTEVA are free and in the public domain; hence its use is unrestricted, thus making the technologies available to the widest possible audience.

- provides access to global computational resources. Once connected to the Internet, GAs automatically try to connect to other appliances and resource pools around the world; thus, providing the user the capability of running ensembles of simulations with ease. However, rather than access global resources, users can also setup their own "virtual clusters". For example, resources within their own LAN can be connected through a secure virtual private network to provide a larger pool of resources without the need of travelling across potentially low bandwidth WAN connections.

- provides an educational environment useful for students of coastal science, cyberinfrastructure, and transportation engineering. For example, coastal science students can better understand how storm surge impacts a domain given storm strength, domain shape, etc. Cyberinfrastructure students can focus on the technical details of the GA itself along with the MTEVA's web interfaces, databases and scripting technologies used behind the scenes. Finally, the transportation engineering student could investigate how the use of lane reversal can be optimized during a storm event.

- illustrates a platform that could be used for other educational and outreach activities. The transportation engineering application presented herein is but one of many possible applications that could be built with GA technology. With the application details presented in this paper combined with the more detailed low-level documentation provided on the Internet, users can readily design their own appliances.

- is simple to setup and use even though the system is composed of many individual components. There is no effort required to get any individual model compiled, library installed, or other setup activity required. Although the system uses a Linux operating system, it will run equally well on a M. S. Windows or Linux Desktop. Because the models, optimization engine, pre- / post-processing scripts, etc. are pre-bundled within the VM, getting the system up-and-running is limited only to get the appropriate VMM installed and the MTEVA started.

- is shown to facilitate learning about key science topics (storm surge and inundation, optimization, and transportation engineering) and thus enhance educational outcomes based on the results of a survey of graduate students who experimented with the MTEVA themselves.

APPLICATION TO A REAL DOMAIN

While the simple domain and transportation network is suitable for demonstrating most basic educational concepts, there is a benefit in applying the MTEVA to a real physical domain. In addition to providing more robust educational lessons, the MTEVA has the potential to be used by regional transportation planners to better understand how specific coastal highways and bridges will be affected by inundation; thus, potentially enabling a more robust transportation system. Additionally, with further study, longer term issues such as sea level rise could be incorporated.

Initially, various sites in the State of Florida were targeted as the storm surge model used in this study, CH3D-SSMS, has been applied to almost all its major estuaries and lakes, including Sarasota, Tampa, Florida and Biscayne Bays, Charlotte Harbor, Indian River Lagoon, and St. Johns River. However, the Jacksonville (Florida Department of Transportation District 2) metropolitan area of Florida will be used in a future CMS funded effort due to its susceptibility to tropical storms, large population base and extensive multimodal transportation networks. Much of needed transportation network data for Florida that would be needed for simulating these areas can be obtained from the Florida Department of Transportation's Roadway Characteristics Inventory (RCI) system maintained by the Transportation Statistics Office (TranStat).

Expansion of the MTEVA from a relatively simple hypothetical domain, to this significantly more complicated region represents a unique challenge to both the simulation of storm surge and inundation and the optimization of the transportation network, which are both orders of magnitude larger in size. As part of this effort, probabilistic surge, inundation and transportation infrastructure risk maps will be developed for the region based on historical climatological data under present data conditions as well as under future conditions expected under global climate change.

FUTURE SURVEY PLANS

With a preliminary survey complete, plans are being develop to survey a larger group although there is not sufficient time to complete this survey as part of this project. Specifically, this effort would be to target graduate students in other programs (engineering/non-engineering majors), undergraduates and non-academic community stakeholders who have expressed interest in the technology. In addition, it would also be interesting to investigate the relationship between the academic quality of the student (e.g. grade point average) and their view of the MTEVA.

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APPENDIX A – MODEL INTERCHANGE FILES

(Version 7/15/2010)

An overview of the input/output files is shown in Table 6
.

Table 6 Input/Output File Description

Model	File Type	Filename	Description
Storm Surge (S.S.)	Input from user	fort.4, fort.15, fort.32, … ch3d_road_network.in	S. S. Input files Network description
	Output to plot	fort.24, fort.25, fort.28, …	S. S. Output files
Exchange Files	Output from S. S. / Input to N. O.	node_status_YYYYMMDD_HHMM.txt flow_YYYYMMDD_HHMM.txt	Node status Connectivity matrix
Network Optimization (N.O.)	Input from user	capacity.txt demand.txt safety.txt	Network capacity Network demand List of safety nodes
	Output to plot	result_YYYYMMDD_HHMM.txt safety_YYYYMMDD_HHMM.txt feasibility_YYYYMMDD_HHMM.txt	Resulting network use Result at safety nodes Feasibility of solution

ch3d_road_network.in

This file consists of the following:

number of nodes and number of connections (one way roads)
X(i), Y(i) (i=1,Nodes) - geographical locations of nodes (1 to Nodes)
Node1(i), Node2(i), Type(i) (i=1,Connections) - establishes connection between two nodes and
        sets a type of the connection (1 = road, 2 = bridge)

Roads are indestructible, while bridges can be destroyed, roads follow topography and road becomes unusable if at any location of the road the flood reaches FloodThreshold value (for this exercise FloodThreshold = 30cm) if at any point of time later on the flood retreats – the road becomes usable again. The bridges are considered to have their own elevation (set to 1 meter for this exercise), however, once the water level reaches the bridge not only it becomes unusable it's also considered "destroyed" and cannot become operational again unlike the road can.

Sample file:

```
# NODES, CONNECTIONS
 18  24
   1000.00        28000.00
  38000.00        30000.00
  22000.00        53000.00
   3000.00        78000.00
  33000.00        78000.00
  55000.00        78000.00
  88000.00        78000.00
 110000.0         78000.00
  88000.00        68000.00
  71500.00        43000.00
 110000.0         43000.00
  88000.00        38000.00
  71500.00        28000.00
  82500.00        28000.00
  99000.00        28000.00
 110000.0         28000.00
  42500.0         50000.00
  58500.0         50000.00
         3                17        1
        17                18        2
        18                10        1
         1                 2        1
        13                14        1
        14                15        1
        15                16        1
        13                10        1
         1                 3        1
         2                 3        1
         1                 4        1
         4                 5        1
         5                 6        1
         6                 7        1
         7                 8        1
         3                 5        1
         7                 9        1
         8                11        1
        11                16        1
        12                15        1
         9                12        1
        10                11        1
        12                14        1
         6                10        1
```

nodestatus_YYYYMMDD_HHMM.txt

The file consists of the following:

Number of nodes
NodeStatus(1)
NodeStatus(2)
…
NodeStatus(NumberOfNodes)

Table 7 Description of NodeStatus values.

NodeStatus	Description
1	The node is connected to 1 or more nodes via an arc
2	The node is isolated and no longer has any connections but may become connected again at some point in the future (e.g. a flooded road)
3	The node has been destroyed and will never again be connected to any other nodes (e.g., a road that has been washed away). This condition is assumed to occur when flooding is greater than 50 cm.

Sample file:

```
18
 2
 3
 1
 1
 1
 1
 1
 1
 1
 1
 1
 2
 3
 3
 3
 3
 3
 3
```

flow_YYYYMMDD_HHMM.txt

The file contains a connectivity matrix at a given time, it consists of

Number of nodes
Connectivity Matrix

A matrix (Nodes x Nodes) which defines connections from Node(i) (row) to Node(j) (column).

Table 8 Description of connectivity values.

Matrix value	Description
0	Nodes are unconnected
1	The nodes are connected.

Sample file:

```
         18
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 1 0 1 0 0 1 0 0 0 0 0 0 0 0
 0 0 0 0 0 1 0 1 1 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0
 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

capacity.txt

This file contains capacity of each road, the structure is the same as the previous file, but numbers signify capacity of each arc.

Table 9 Description of capacity values.

Matrix value	Description
#	Capacity of a given arc.

Sample file:

```
 0   7   8 10   0   0   0   0   0   0   0   0   0 0 0 0 0 0
 7   0   9   0   0   0   0   0   0   0   0   0   0 0 0 0 0 0
 8   9   0   0 15   0   0   0   0   0   0   0   0 0 0 0 8 0
10   0   0   0 10   0   0   0   0   0   0   0   0 0 0 0 0 0
 0   0 15 10   0 10   0   0   0   0   0   0   0 0 0 0 0 0
 0   0   0   0 10   0 10   0   0 15   0   0   0 0 0 0 0 0
 0   0   0   0   0 10   0 10 10   0   0   0   0 0 0 0 0 0
 0   0   0   0   0   0 10   0   0   0 10   0   0 0 0 0 0 0
 0   0   0   0   0   0 10   0   0   0   0 10   0 0 0 0 0 0
 0   0   0   0   0 15   0   0   0   0 15   0 10 0 0 0 0 8
 0   0   0   0   0   0   0 10   0 15   0   0   0 0 0 8 0 0
 0   0   0   0   0   0   0   0 10   0   0   0   0 5 5 0 0 0
 0   0   0   0   0   0   0   0   0 10   0   0   0 8 0 0 0 0
 0   0   0   0   0   0   0   0   0   0   0   5   8 0 7 0 0 0
 0   0   0   0   0   0   0   0   0   0   0   5   0 7 0 7 0 0
 0   0   0   0   0   0   0   0   0   0   8   0   0 0 7 0 0 0
 0   0   8   0   0   0   0   0   0   0   0   0   0 0 0 0 0 5
 0   0   0   0   0   0   0   0   0   8   0   0   0 0 0 0 5 0
```

demand.txt

This file defines demand of each node

Table 10 Description of capacity values.

Column value	Description
#	Demand of each node

Sample file:

```
20
25
10
0
0
0
0
0
10
5
8
8
5
5
10
5
0
0
```

safety.txt

The file consists of the following:

Number of nodes
SafetyNode(1)
SafetyNode(2)
…
SafetyNode(NumberOfNodes)

Table 11 Description of SafetyNode values.

NodeStatus	Description
0	The node is not a safe destination
1	The node is a safe destination

Sample file:

```
18
 0
 0
 0
 1
 1
 1
 1
 1
 0
 0
 0
 0
 0
 0
 0
 0
 0
```

feasibility_YYYYMMDD_HHMM.txt

The file consists of the following:

KKT.PE-Feasibility InfeasibleNode
KKT.PB-Feasibility InfeasibleNode

Table 12 Description of the Feasibility file.

KKT.PE	If infeasible, Node #, else 0
KKT.PB	If infeasible, Node #, else 0

Sample files
Feasible Solution:

```
KKT.PE  0
KKT.PB  0
```

Infeasible Solution:

```
KKT.PE  0
KKT.PB  2
```

result_YYYYMMDD_HHMM.txt

The file contains a result matrix at a given time, it consists of

Number of nodes
Result Matrix

A matrix (Nodes x Nodes) which defines connections from Node(i) (row) to Node(j) (column).

Table 13 Description of result values.

Matrix value	Description
0	Nodes are unconnected
#	The result between the two nodes. Negative value implies flow in the opposite direction (contraflow)

Sample file:

```
    18
    0    0    7   10    0   0   0    0    0    0    0   0   0   0    0    0   0   0
    7    0    9    0    0   0   0    0    0    0    0   0   0   0    0    0   0   0
    0   -9    0    0   15   0   0    0    0    0    0   0   0   0    0    0   5   0
  -10    0    0    0    0   0   0    0    0    0    0   0   0   0    0    0   0   0
    0    0  -15    0    0   0   0    0    0    0    0   0   0   0    0    0   0   0
    0    0    0    0    0   0   0    0    0  -15    0   0   0   0    0    0   0   0
    0    0    0    0    0   0   0    0  -10    0    0   0   0   0    0    0   0   0
    0    0    0    0    0   0   0    0    0    0  -10   0   0   0    0    0   0   0
    0    0    0    0    0   0   8    0    0    0    0   0   0   0    0    0   0   0
    0    0    0    0    0   8   0    0    0    0    0   0   0   0    0    0   0   0
    0    0    0    0    0   0   0   10    0    4    0   0   0   0    0   -8   0   0
    0    0    0    0    0   0   0    0    8    0    0   0   0   0    0    0   0   0
    0    0    0    0    0   0   0    0    0    9    0   0   0   0    0    0   0   0
    0    0    0    0    0   0   0    0    0    0    0   0   4   0    1    0   0   0
    0    0    0    0    0   0   0    0    0    0    0   0   0   0    0    4   0   0
    0    0    0    0    0   0   0    0    0    0    8   0   0   0   -7    0   0   0
    0    0    0    0    0   0   0    0    0    0    0   0   0   0    0    0   0   5
    0    0    0    0    0   0   0    0    0    5    0   0   0   0    0    0   0   0
```

safety_YYYYMMDD_HHMM.txt

The file consists of the following:

Number of nodes
SafetyValue(1)
SafetyValue(2)
…
SafetyValue(NumberOfNodes)

Table 14 Description of SafetyValue values.

SafetyValue	Description
0	The node is not a safe destination
#	The resulting population at each safety node

Sample file:

```
18
 0
 0
 0
20
30
23
18
20
 0
 0
 0
 0
 0
 0
 0
 0
 0
 0
```

APPENDIX B – SPECIFICATIONS OF THE HYPOTHETICAL DOMAIN

The hypothetical study domain consists of a simple coastline, with a narrow inlet and large bay (Figure 10). A 115 km x 100 km orthogonal grid (115x100 cells) was created using a grid spacing of $\Delta x=\Delta y=1$ km. Spatial coordinates are based on a UTM coordinate system while bathymetry and topography are referenced to the NAVD88 vertical datum. Initial water level in the domain is set to 0 m; thus, the elevation at the shoreline is also set to 0 m. The bathymetry extends 24 km linearly offshore using a slope of 1:100. Topography linearly increases inshore to a maximum elevation of 1.8 m. The domain also contains an inlet-bay system. The width of the bay is 13 km and the length is 42 km while the width of the inlet is set to 5 km.

A simple transportation network was overlaid into the study domain which contains 18 nodes and various interconnecting arcs. The arc which crosses the bay is defined as a bridge while the remaining arcs are roads. Additionally, a hypothetical set of demands (Figure 11) and capacities (Figure 12) was created to test the network model. The critical values for flooding were defined as $H_{Ncr}=50$ cm and $H_{Acr}=30$ cm and the elevations of the arcs were defined as $R_A=0$, and $B_A=1$ m. The critical value of wind speed on a bridge, W_{Acr}, is set to 45 mph.
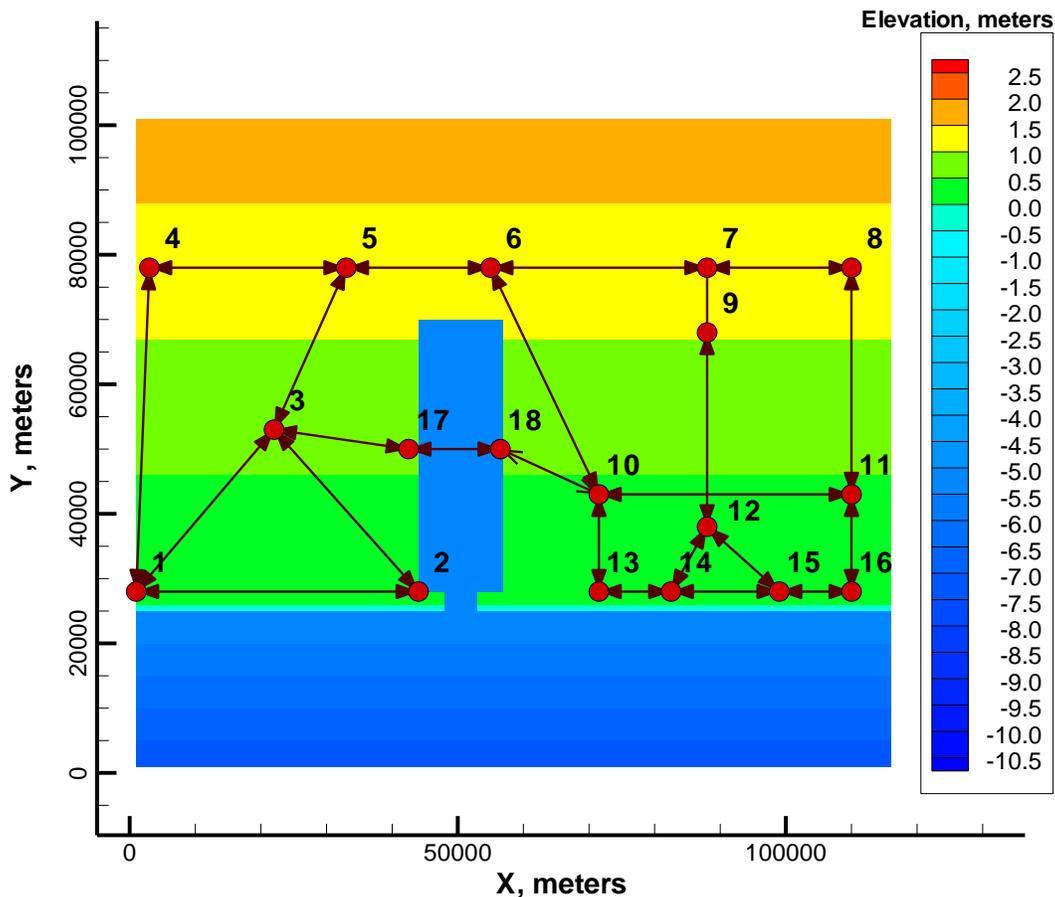

Figure 10 Hypothetical study domain and road network.

Figure 11 Node demand.

Figure 12 Arc capacity.