A SIMULATION TOOL FOR HIGH-FIDELITY MODELING OF COMPLEX LOGISTICAL NETWORKS

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ABSTRACT

Ports are a vital component of the nation's transportation system. It is vital for ports to address the various security risks associated with port operations, by analyzing these risks, adopting strategies to prevent incidents and developing mitigation strategies to deal with incidents if they do occur. Simulation presents an ideal opportunity to model current port operations, and then to perform what-if analyses by improving/adding infrastructure and resources to determine its effectiveness on improving cargo throughput and relieving bottlenecks. Simulation also provides a cost-effective and non-invasive method to study the impact of disruptive incidents. A simulation tool is presented here that enables the Virginia Port Authority (VPA) to have a system-level view of cargo operations for the entire Hampton Roads region. It also allows planners in determining the cause and effect relationships between disruptive events (natural catastrophes or terrorist acts) and port and transportation infrastructure, to plan for threat contingencies.

Keywords: Decision-support system, Discrete-event simulation, security analysis, programmable processes.

1. INTRODUCTION

Ports form a vital component of the national transportation infrastructure. They are a logistical focal point of the system that, if disrupted, will greatly slow commerce and the have significant effects on the quality of life of the citizens, due to the unavailability of items that we require in our daily life. Ports need to investigate and adopt security strategies both to prevent disruptive incidents, and to mitigate their effect, if incidents do occur. It is also important for ports to maintain, if not increase the volume of cargo flowing through them in these times of economic downturn. The security strategies should ideally have minimal effect on the flow of cargo through a port, so that normal operations flow smoothly.

Simulation presents the opportunity to comprehensively model the current state of operations in a complex logistical network. The Virginia Port Authority (VPA) required a simulation tool to model cargo flow operations within the Port of Virginia (POV). It also required the tool to model the impact of security measures and operational disruptions (natural catastrophes or terrorist acts) from a regional perspective.

The simulation tool presented here, the Port Analysis Simulation (PAS), models the complete multimodal logistical network for the Port of Hampton Roads. PAS connects together relevant cargo terminals (seaside and inland ports, rail yards, etc.) and the transportation infrastructure between these terminals, thereby presenting a system-level view of cargo operations for the entire Hampton Roads region. It allows VPA operational planners to observe cargo flow activity within the entire system as part of the current state of operations and study the potential impact of changes to operations before actually implementing the changes. PAS also enables planners in analyzing the cause and effect relationships between disruptive events (natural catastrophes or terrorist acts) and port and transportation infrastructure. Stakeholders can use the analyses for collaboration and maritime security awareness, risk management and planning, studying the economic impact of potential disruptions and to plan for threat contingencies.

PAS is a customized instantiation of MYMIC's Scalable End-to-End Logistics Simulation (SEELS™) architecture. The PAS application consists of a Graphical User Interface (GUI) that enables a user to design and design and configure a solution, execute the solution using the SEELS Simulation Core, and view the simulation output for analysis. This interaction is shown in Figure 1.

Section 2 and 3and provide a complete description of the PAS tool. Section 4 describes the SEELS simulation core architecture and capabilities. Section 5 provides some example analyses performed using PAS, including the superior performance of PAS. Section 6 describes related work and Section 7 provides conclusions for this work.

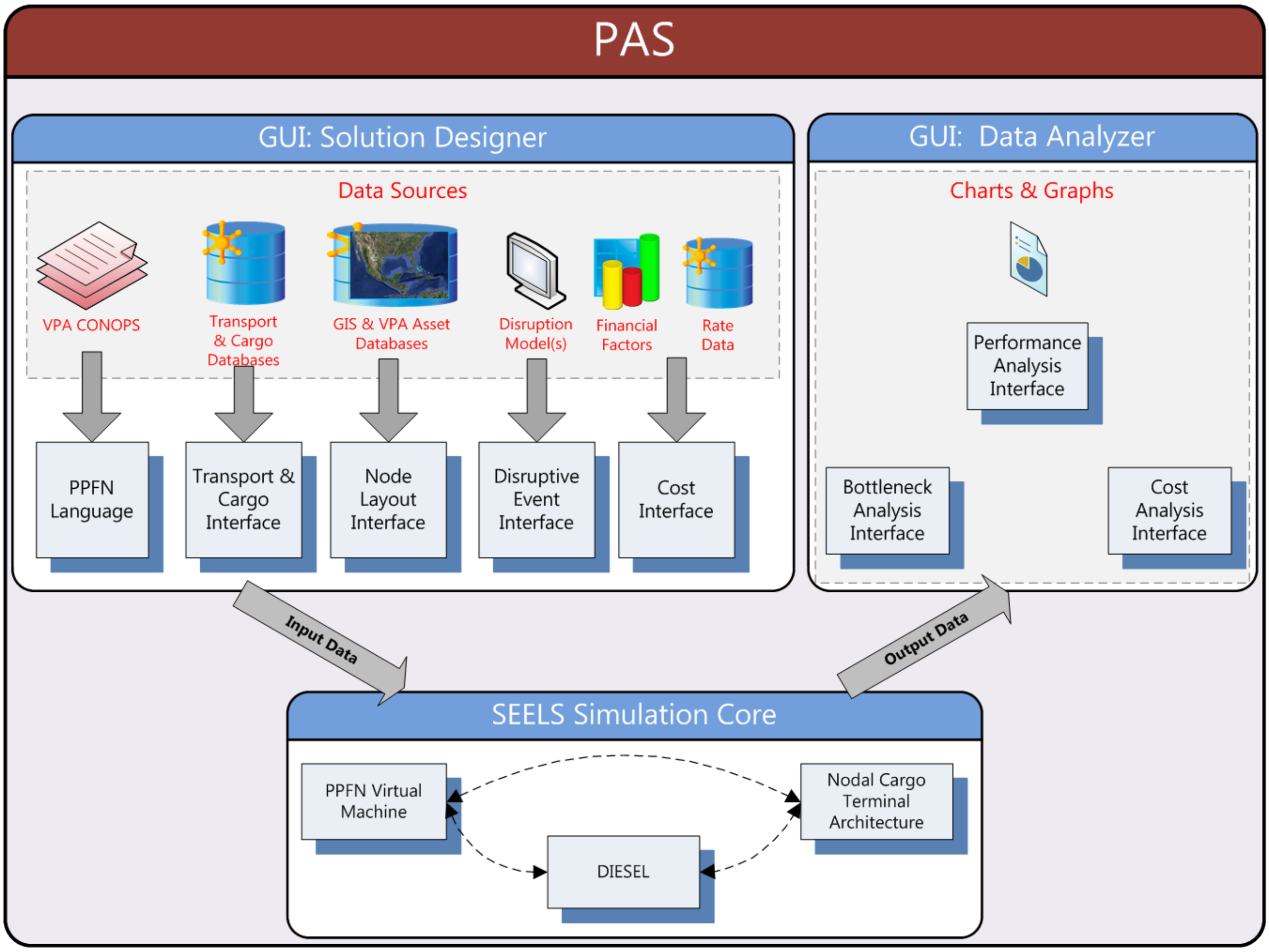

Figure 1: Port Analysis Simulation (PAS)

2. PORT ANALYSIS SIMULATION (PAS)

The Port Analysis Simulation (PAS) models commercial cargo flow operations through all of the facilities belonging to the Virginia Port Authority (VPA), including the Port of Virginia (POV) and the Virginia Inland Port, and presents a system-level view of cargo operations. Terminals within the POV that are modeled within PAS include:

- Norfolk International Terminal (NIT)
- APM Terminals Virginia (APMT)
- Newport News Marine Terminal (NNMT)
- Portsmouth Marine Terminal (PMT)

VPA uses PAS to model their current operations across all of its terminals to study the normal state of operations and validate current cargo throughput. PAS is capable of determining cargo throughput capability using current assets, resources, and business processes. It tracks utilization of critical resources as identifies potential bottlenecks and limiting resources to cargo movement through the network.

2.1. Operational Analyses

Once a baseline model has been established using current infrastructure and resources, VPA can perform what-if analysis on the impact of adding new infrastructure (new berths, or increases in staging capacity) and/or new resources (straddle carriers, container cranes, etc.). VPA can use this analysis to determine the impact that the increased capability has on performance metrics such as, cargo throughput and truck turnaround times. The analysis can also be used to calculate Return on Investment (ROI) metrics before significant investment decisions are made. VPA can also model proposed changes to its business processes and determine the impact (positive or negative) on the same performance metrics, before actually implementing the changes. VPA can also use PAS to model the planned Craney Island Terminal scheduled to be operational after 2020 (Virginia Port Authority 2010) using its proposed resources and infrastructure to simulate the flow of projected cargo through the terminal to validate current assumptions and identify future requirements.

VPA is also preparing for the Panama Canal expansion, when the capacity of the Canal will be doubled enabling the mega container ships to call on ports on the East Coast. VPA aims to draw a large portion of this container traffic to POV, and has plans to use PAS to model the flow of cargo arriving by the large ships, offloading most if not all of the cargo at

POV, and then transporting the cargo via rail and trucks to their destinations without requiring the ships to make additional ports of call on the East Coast.

2.2. Security Analyses

PAS supports two types of security analyses and assists VPA operational planners to develop contingency plans for various disruptive scenarios and plan for new security measures. First is proactive or preventive, where areas and operations within the ports and the transportation infrastructure are analyzed to identify their impact on operations should they be disrupted. Planners then develop efforts to protect those capabilities using different methods such as new security measures, increased container and truck inspections, etc. PAS allows planners to insert proposed inspection stations anywhere within the port facilities (between berth and staging, or between staging and the gates) and determine the slowdown impact that it has on cargo flow. Planners can also use PAS to determine capability requirements for inspection stations (e.g. 40 inspections per hour) to minimize the impact on cargo flow.

The second type is to analyze responses to disruptive incidents if they do occur. PAS models a disruption in the operations of a terminal by appropriately reducing the allocation and number of resources, available infrastructure, and processing capabilities of that particular terminal, either permanently or for a specific duration of time within the simulation. The impact of response strategies to alleviate slowdown in cargo flow can then be analyzed including cleanup/recovery procedures and rerouting of cargo to maintain operational effectiveness. This demonstrates the effect on a terminal and the potential ripple effect on other terminals within the region as the logistical network adapt to sustain cargo flow.

PAS can also be integrated with other models (traffic models, weather models, etc.) to form a complete federation that includes all ports and transportation networks in the region and accounts for the man-made and natural variables that can impact port operations. It can also be interfaced with validated disruption models that can automatically inject stimuli to modify the behavior of the simulation.

3. PAS INTERFACE

The PAS Graphical User Interface (GUI) is a standalone windows application that enables a user to design a solution (including scenarios and profiles), execute the solution using the SEELS Simulation Core, and view the simulation output for analysis. The PAS GUI provides an intuitive graphical interface using maps, GIS data and rich, interactive charts. It is implemented using Windows Presentation Foundation (WPF), and follows the Model-View-View Model (MVVM) design pattern (Smith 2009) as shown in Figure 2. The GUI is designed to match the scalability of the SEELS simulation core by utilizing a highly configurable model that is defined by user provided data.

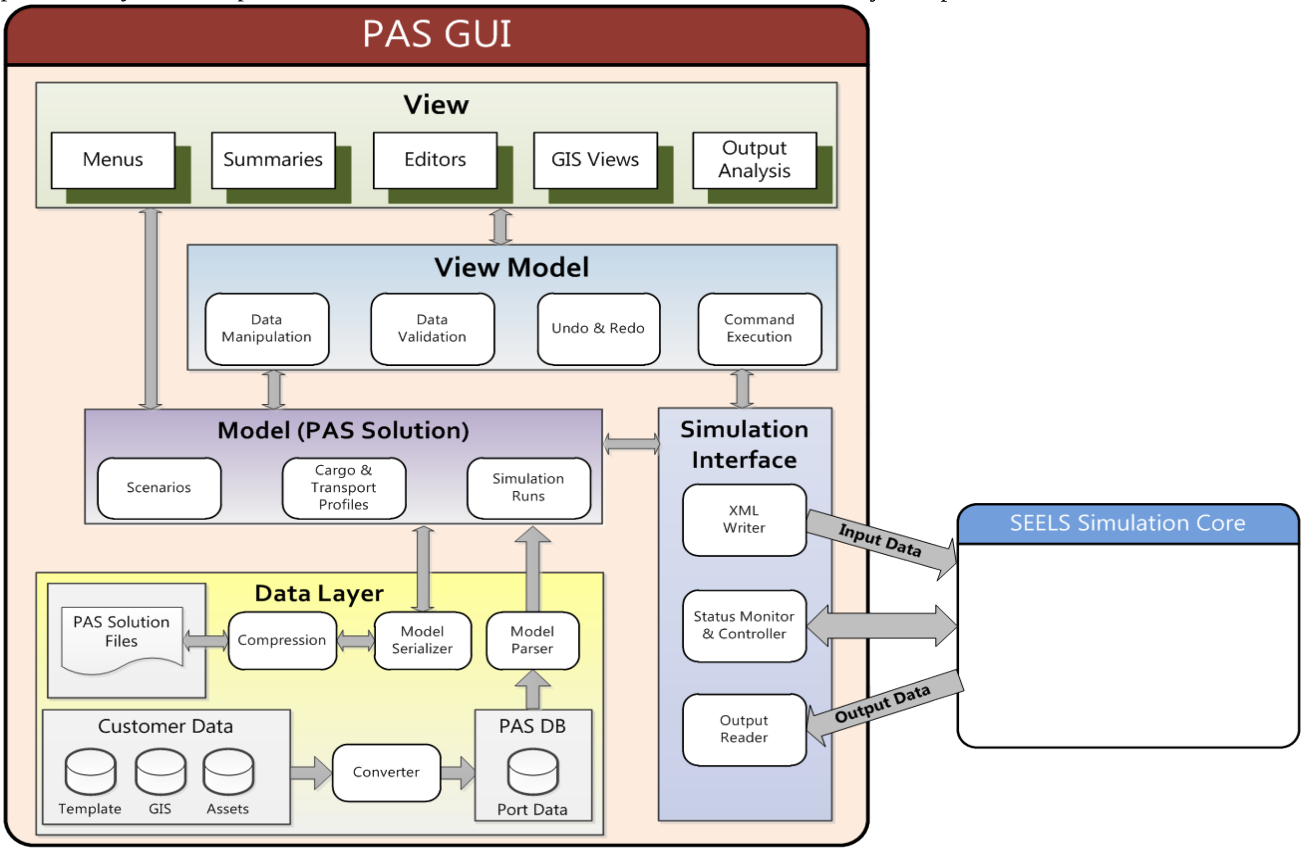

Figure 2: PAS GUI Design

3.1. Solution Designer

The GUI uses a variety of data sources including GIS data on current port infrastructure, asset data on current resources as well as cargo and transport classes that are handled by the logistical network. The GUI also includes a template that defines the structure of the different types of nodes (inland ports, seaports, automated container terminals, etc.). All this data is then used to create PAS Solutions. Solutions are made up of scenarios, cargo/ transport profiles, and simulation runs. Solutions are stored as compressed XML files and can be easily copied and shared between users.

Scenarios are a model of a complete logistical network, consisting of any number of ports, terminals, operational areas, and resources. Scenarios also define the time it takes to travel between each node (transit times) and the time it takes to complete each port operation (processing times). Maps of ports are provided using an ArcGIS map provider and polygons representing infrastructure are generated within the interface using the ESRI Shapefile format. Polygons can also be created and modified in the GUI, enabling a user to create new areas, terminals, ports, etc.

Cargo and transport profiles define the cargo and transports that flow through the logistical network during the simulation. This data can either be created in the GUI or can be ingested from data sources, such as cargo manifests. This generates arrival events, which define the arrival time, quantity, and cargo load of each individual transport. Transports can arrive empty or loaded with a mix of cargo headed for different destinations.

A simulation run consists of a single scenario and one or more transport profiles that are executed by the SEELS Simulation Core. The output data generated by the SEELS Simulation Core are stored as part of the simulation run.

3.2. Output Analysis

PAS models cargo and transports at the individual entity level and the output data collected during a simulation run (or iteration) can be used for extensive after-action reporting and visualization. Output data can be captured for every node within the logistical network for any measurable metric. Typical output includes infrastructure and resource cost and utilization, as well as cargo and transport throughput and timing. The data can be analyzed and compared to previous runs in rich charts and graphs that visualize and filter the data. Users can also easily drill down from a high level view of the entire logistical network to data on a specific operational area within a terminal.

4. SEELS SIMULATION CORE

The Scalable End-to-End Logistics Simulation (SEELS™) technology supports the modeling of complex logistical networks for commercial, military, and government customers for use in planning, analysis, and experimentation. For every customer, SEELS models their unique end-to-end logistical network and functions as a decision-support tool to quickly analyze different what-if scenarios. SEELS is a scalable, nodal, and programmable architecture that allows a user to:

- Define the item (cargo/bulk/person) entity level used in the simulation
- Scale level of fidelity (as required) to model a node
- Define the handling processes for a node

SEELS can model people, containers, medicinal equipment or any variety of material as cargo flowing through a logistical network. SEELS also enables planning a complete logistical network at a local, regional, or global level. A network can be composed of any number of logistical nodes of any type. The definition of a node is limited only by the user's requirements; thus, a node may be an entire seaport or a single fueling point along a highway. Typical types include seaports, airports, warehouses, distribution centers, intermediate staging bases, etc. The nodes can be defined at any level of fidelity depending on a customer's unique requirements or availability of data.

A set of nodes can be connected by a variety of transportation links, such as air, sea road, rail, or other means of transportation to model a complete, multimodal end-to-end logistical operation. Further, separate logistical operations can be linked to form an integrated, highly scalable, network-of-networks model. SEELS applies a single-model solution to the end-to-end logistics problem, as a viable alternative to the complexity of a federated solution.

SEELS captures a customer's business rules as processes for the different nodes. The processes dictate how cargo and transports are handled within each node. Processes are not part of the SEELS simulation software; rather they are provided as input just like any other data to the software during a simulation run. This allows processes to be modified easily to support experimentation with changes to business rules.

4.1. Nodal Cargo Terminal Architecture

The architecture is defined as a network of nodes, with the flow of cargo and transports through each node defined by processes. A node can be an inland port, seaport, a terminal within a seaport, or an operational area within either the seaport or a terminal. A node could also potentially represent a whole other network of nodes. This allows a hierarchical structure where individual nodes are defined by the internal processes performed within the node on the cargo and transports and possibly by a new network (network nodes). Multiple network nodes, each modeling a complete seaport, airport or inland port in itself, can be connected together to model an end-to-end cargo flow from a point of origin to a destination (Mathew 2002, Mathew, Leathrum, Mazumdar, Frith and Joines 2005).

For example, PAS defines the Port of Hampton Roads as a seaport node. The seaport node has a network of terminals, including Norfolk International

Terminal, APM Terminals Virginia, Portsmouth Marine Terminal, Newport News Marine Terminal, etc. Each terminal itself is defined in terms of operational areas: the berths, staging, loading areas, etc. The Virginia Inland Port (VIP) is also a network node, without terminals, but has a network of operational areas such as staging areas, rail spurs, loading areas, etc.

The capacities and capabilities of individual nodes are programmable, and so are the processes within them. The architecture is configurable to support different port types, different individual ports, different cargo types, and different transport types. The architecture also supports routing entities through the network. A route is defined by a starting node, a destination node, and a sequence of nodes traversed en route. An important approach to avoid infinite queuing in the interconnection segments is that a node must request the next node in the route before advancing. This provides a level of flow control to aid in the avoidance of deadlock.

4.2. Programmable Processes

Processes for the SEELS simulation are programmable, unlike many applications where processes are hard coded within the simulation. The Programmable Process Flow Network (PPFN) supports defining processes that are input to the SEELS simulation core during simulation run-time (Mathew and Leathrum 2008). PPFN is a process flow programming language that describes the process activities at a cargo terminal. PPFN provides an intuitive approach for an analyst to capture processes by providing the ability to define/edit/modify processes independent of the simulation and provide it as an input to the simulation in the same way other data is input; this makes the tool more responsive to changes in requirements. Moreover, port Subject Matter Experts (SMEs) view operations within a cargo terminal in terms of processes that must be performed in a given situation. PPFN provides a process-oriented interface (in terms of flowcharts) for a discrete-event simulation, with processes being defined as sequences of activities and decisions.

4.3. Programmatic Events

SEELS provides a capability to impact simulation behavior, both negatively and positively at run-time called Programmatic Events. Programmatic events allow an analyst or an external disruption model to program unusual events to occur at specific simulation times, thereby modeling the effect disruptive events such as a chemical, or biological weapon attack into a scenario. These events can change the processing, available resources, capacities, and capabilities of a node or transit times between nodes during simulation run-time. For example, an analyst can program a new berth to become available on day 7, instead of day 0, or a berth and associated resources like cranes to be unavailable from days 2-10 due to a disruptive incident. SEELS can also be interface with other disruption models, to portray the effects of disruptive events on seaport operations, i.e., allowing the capability of the seaport to be degraded as a result of a disruptive event and then be gradually restored over time (Leathrum, Mathew, and Mastaglio 2009).

5. EXAMPLE ANALYSES

A baseline scenario for current cargo operations is developed. This baseline scenario models the container flow through two terminals at POV: NIT and APMT during a week. On an average, 22000 containers (import and export) flow through each terminal during a week. The baseline scenario clears all cargo at NIT by 9 days and at APMT by 10 days. Then different analyses are performed by defining 3 unique use-cases which are described in the following sub-sections.

5.1. Proactive Security Analyses

PAS allows planners to proactively implement security strategies by inserting proposed inspection stations anywhere within the port facilities and assess the impact that it has on cargo flow. In this case, an inspection is inserted right after the gate within the NIT terminal, requiring each truck coming into the terminal to be inspected before proceeding to pick up or drop off containers in the terminal (Figure 3). If 10 concurrent inspections can be performed at the station, using an inspection time (Triangular distribution with a minimum time of 2 minutes, maximum time of 3 minutes and most likely time of 4 minutes), then cargo clearance at NIT is delayed by approximately 3 days compared to the baseline scenario. The comparison between cargo clearances is shown in Figure 4. However, if the number of concurrent inspections that can be conducted is increased to 40, then cargo clearances at NIT is delayed by just 1 day.

Planners can then determine capability requirements for inspection stations and make decisions on whether extra investments are required to improve cargo clearances. Planners can also analyze other data such as area and resource utilization and transport turnaround times in their decision-making process.

5.2. Reactive Analyses

PAS also supports planners in developing response strategies to disruptive incidents if and when they do occur. In this use-case, an incident occurs at APMT that damages a crane rendering another adjacent crane and 2000 feet of berth space unusable for 6 days. This reflects an actual incident that occurred at APMT, where the disruption lasted for longer than 6 days (McCabe 2011). The disruption only delays cargo clearance at APMT by 2 days, even with reduced cargo handling capacity (Figure 5) indicating that APMT has the ability to deal with the disruption. However, if the disruption lasts longer, VPA can use PAS to develop mitigation plans by developing scenarios to analyze the impact of diverting traffic to its other terminals. This would allow other VPA terminals to pick up the slack, while APMT is brought back to its full operational capacity.

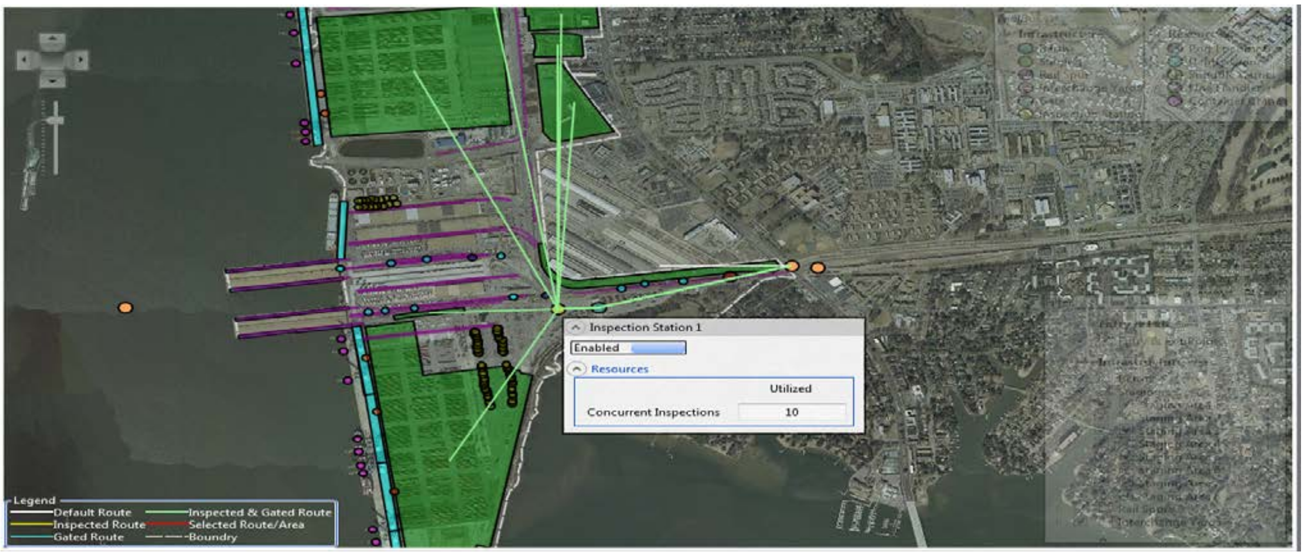

Figure 3. Security Inspection at NIT

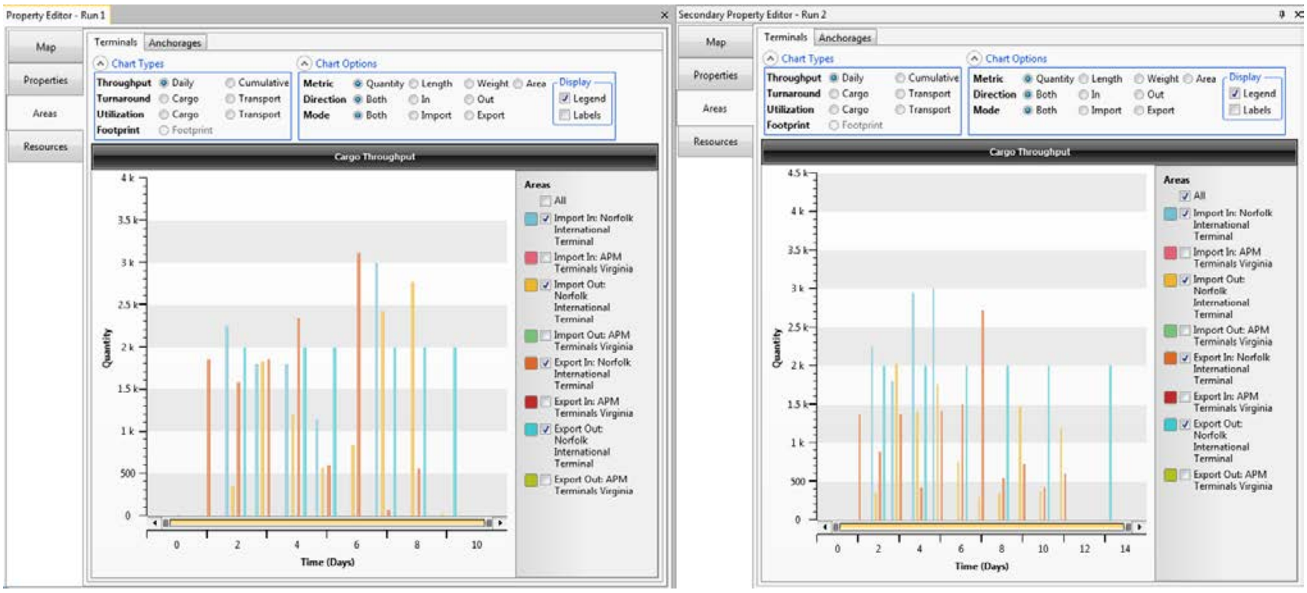

Figure 4. Cargo clearance comparison between baseline scenario and scenario with inspection

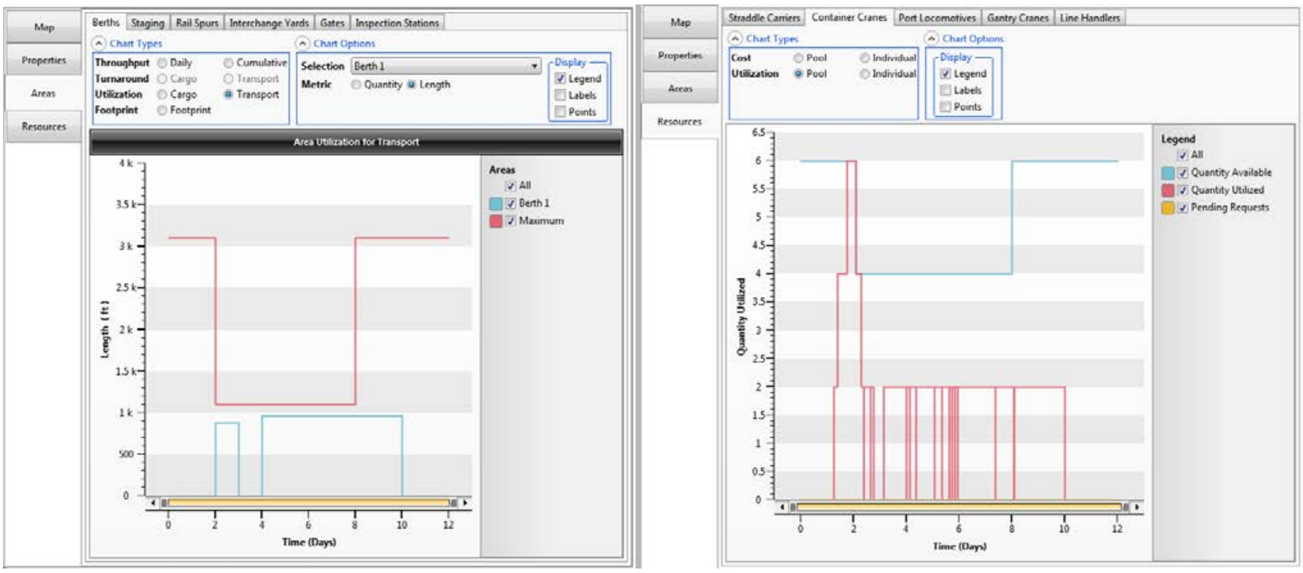

Figure 5. Crane accident scenario at APMT

Figure 6. Proposed Craney Island Terminal next to APMT and NIT

5.3. Craney Island Terminal

PAS can also support VPA in modeling its proposed Craney Island Terminal scheduled to be operational after 2020 (Virginia Port Authority 2010). Planners can use proposed designs including resources and infrastructure to create a complete model of the terminal. PAS provides a simple, intuitive, click-and-drag interface to design new infrastructure, including the ability to create areas (berths, staging areas, rail spurs, etc.) and add resources (straddle carriers, cranes, forklifts, etc.). Planners can then simulate the flow of projected cargo through the terminal and analyze the results to validate current assumptions, detect bottlenecks, and identify future requirements. The model can be refined along with design changes to continuously analyze and validate the design and investment decisions. It also provides VPA with independent and validated analytics to use in discussions with different stakeholders.

5.4. Simulation Performance

The SEELS simulation core has been designed and developed for portability across alternative computing systems. The software code is written as an ANSI Standard C++ implementation, with a key focus on execution speed and low memory usage. It also uses a high-performance, C++ implementation of the Distributed, Independent-platform, Event-driven, Simulation Engine Library (DIESEL) (Mathew 2007), as its underlying simulation executive.

Due to the high-performance of the SEELS simulation core, PAS is capable of simulating the flow of over 40000 pieces of cargo through the VPA network in under 20 seconds, executing approximately 1.6 million events in that time. PAS is also capable of simulating the flow of over a million pieces of cargo at an individual entity level of detail in under 30 minutes.

6. RELATED WORK

There exist a plethora of commercial cargo terminal simulation models and tools modeling ports all over the world (Ballis and Abacoumkin 1996; Bruzzone and Signorile 1998; Dzielinski, Amborski, Kowalczuk, Sukiennik, and Pawlowski 2002; Gambardella, Rizzoli, and Zaffalon 1998; Hayuth, Pollatschek, and Roll 1994; Kia, Shayan, and Ghotb 2002; Kozan 1997; Merkuryev, Tolujew, Blymel, Novitsky, Ginters, Viktorova, Merkuryeva, and Pronins 1998; Merkuryeva, Merkuryev, and Tolujew 2000; Ramani 1996; Shabayek and Yeung 2002; Van Hee and Wijbrands 1988; Yun and Choi 1999). These tools differ widely in their objectives, complexity, level of detail and operational factors taken into consideration due to the variation in the questions that a particular model attempts to answer as well as the model's fidelity. There are also custom tools developed by ports or logistics consulting firms operating on behalf of ports using software such as Arena, ProModel, etc. Most of these tools are limited as they are designed around the commercial activities of a specific port/terminal with very limited capabilities to adapt it to another port without needing significant development. PAS. Developed for VPA, can be easily adapted to any port in the world by populating the tool with GIS data (for infrastructure), asset data (for port resources), business rules for cargo handling, and cargo data. The underlying technology supports modeling any port without requiring software changes.

7. CONCLUSION

The Port Analysis Simulation (PAS) tool presented here supports VPA in modeling cargo operations across all of its terminals. PAS provides capabilities to model VPA facilities and assets at a high level of fidelity and supports analyzing different performance metrics for improving the efficiency of current VPA operations. PAS also supports VPA in performing operational what-if analyses on the impact of adding new infrastructure or resources and calculate Return on Investment (ROI) metrics before significant investment decisions are made. PAS also enables VPA to adequately prepare for major operational changes such as building the new Craney Island Terminal and the arrival of larger ships after the Panama Canal expansion, by providing a robust, configurable, and high-performance modeling and analysis capability. PAS can be easily adapted to other ports all around the world by populating the tool with appropriate data about the port, without requiring any software development.

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