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Defending the Pittsburgh Waterways Against Catastrophic Disruption

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NAVAL POSTGRADUATE SCHOOL

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THESIS

DEFENDING THE PITTSBURGH WATERWAYS AGAINST CATASTROPHIC DISRUPTION

by

Joshua J. Onuska

June 2012

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DEFENDING THE PITTSBURGH WATERWAYS AGAINST CATASTROPHIC DISRUPTION

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis develops an Operator's Model that mimics the real-world behavior of coal transport in the Port of Pittsburgh and allows for systematic investigation of "what if" disruption scenarios. We model the multi-modal flow of coal using a network of nodes and arcs representing river transport, with support from a surrounding system of rail lines and roads. Each mode of shipment has finite capacities with varying costs. Our model routes flows in order to satisfy contracted supplies and demands at minimum transportation cost. We use 2009 coal shipment data provided by the United States Army Corps of Engineers to drive delivery patterns. We focus our attention on the Monongahela River, which carries a significant amount of coal through our system. We employ Defender-Attacker-Defender techniques to assess critical infrastructure in the context of an intelligent adversary, such as a terrorist, who seeks to damage the system so as to maximally increase its operating cost. This allows us to assess the relative importance of critical system components in order to help the United Stated Coast Guard identify where to focus their attention.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Attacker-Defender
AOI	Area of Interest
ARMOR	Assistant for Randomized Monitoring Over Routes
ASME	American Society of Mechanical Engineers
C/ACAMS	Constellation/Automated Critical Asset Management System
CI/KR	Critical Infrastructure / Key Resources
DAD	Defender-Attacker-Defender
DHS	Department of Homeland Security
DOT	Department of Transportation
GAMS	Generalized Algebraic Modeling System
GAO	Government Accountability Office
GUARDS	Game Theoretic Unpredictable and Randomly Deployed Security
HSAC	Homeland Security Advisory Council
HSC	Homeland Security Council
IRIS	Intelligent Randomization in Scheduling
MSRAM	Maritime Security Risk Analysis Model
MTS	Marine Transportation System
MTSA	Maritime Transportation Security Act
NIPP	National Infrastructure Protection Plan
NRC	National Research Council
PPC	Port of Pittsburgh Commission
PRA	Probabilistic Risk Assessment

PROTECT	Port Resilience Operational / Tactical Enforcement to Combat Terrorism
PWCS	Ports, Waterways, and Coastal Security
RAMCAP	Risk Analysis and Management for Critical Asset Protection
TRAM	Terrorism Risk Assessment and Management
TVC	Threat, Vulnerability, and Consequence
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
VBA	Visual Basic for Applications

EXECUTIVE SUMMARY

The United States (U.S.) economy is dependent upon coal to produce low cost energy and to manufacture steel. The Three Rivers region of Pittsburgh, Pennsylvania—consisting of the Ohio River, the Allegheny River, and the Monongahela River—sits on one of the richest coal reserves in the U.S.. The Port of Pittsburgh stretches over more than 300 miles of river and supports an extensive coal mining and coal consuming industry. Nearly $9 billion of commerce flows through this river system annually, making it the second largest inland port in the U.S. and a valuable target for terrorist attack. The United States Coast Guard (USCG) is responsible for safe, uninterrupted transport (and coordinated security) along these inland waterways, and this port is of particular importance to this mission.

Coal is delivered from mines to plants primarily via the river, with support from a surrounding system of rail lines and roads. Transporting coal by barge on river is the most economical and efficient means of delivery. Rail offers a more costly alternative, and trucks on roads are the most expensive method of transportation. Loading and offloading coal are also costly processes. But these costs are small relative to the huge financial loses and catastrophic facility shutdowns that could occur if coal was unable to move from supplier to consumer for an extended period of time.

The primary contribution of this thesis is the development of an Operator's Model that mimics the behavior of coal transport in the Port of Pittsburgh and allows for systematic investigation of "what if" scenarios. We model the multi-modal flow of coal using a network of nodes and arcs. Each mode of shipment has finite capacities with varying costs. Our model routes flows in order to satisfy contracted supplies and demands at minimum transportation cost. We use real-world 2009 data provided by the United States Army Corps of Engineers to drive delivery patterns.

We employ Defender-Attacker-Defender techniques to assess critical infrastructure in the context of an intelligent adversary, such as a terrorist, who seeks to damage the system so as to maximally increase its operating cost. Key assets in our system include dams, which segment the rivers into pools and maintain water levels that

enable navigability; locks, which allow for transit between these pools; bridges, which connect land masses by crossing over rivers; and intermodal transfer equipment, which loads and offloads cargo and facilitates transfer between rivers, roads, and rails.

We focus our attention on the Monongahela River, which carries a significant amount of coal through our system. Our model first analyzes normal operating conditions, routing coal by barge, and then considers the effects of disruptions to the river system. We identify interdictions that result in worst-case disruptions, where "worst-case" means the highest total cost even after the system has rebalanced flows. The model illustrates rerouting behaviors and impact costs associated with operating in this damaged system. This helps us assess the relative importance of critical system components to help the USCG to identify where to focus its attention.

We observe that a single attack on the pool connecting the Monongahela River to the rest of the Pittsburgh Port incurs significant cost increases. Attacking the dam supporting this pool renders the pool useless. Subsequent "next best" attacks also target other dams and eventually some locks. Each disruption to the river unavoidably increases traffic on other modes of transport, increasing overall cost.

We consider two alternative scenarios. First, we analyze a situation in which we assume that the USCG can perfectly protect the dams from attack. Defending dams causes the attacker to target locks instead, thereby decreasing the worst-case cost of an attack on an unprotected system. The second scenario is a situation in which the USCG can perfectly protect both dams and locks. With the water protected, the attacker can only target land-based terminals, rail segments and road segments. However, an attacker still has the ability to isolate a major coal supplier from the network by interdicting river, rail, and road intermodal transfer arcs connecting the supplier to the rest of the world. Because our model highly penalizes such infeasibilities, the cost skyrockets, as the coal supplier is unable to move cargo onto the system.

Our model can be applied to others ports within the Inland Waterway System, however doing so will require significant effort to develop the appropriate input data and exercise various what-if scenarios of interest.

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I. INTRODUCTION

The United States relies on low-cost transportation of goods. Bulk shipment of commodities is vital to the U.S. economy and its national security. A complicated network of rivers, rail lines, and roads enable the surface movement of large quantities of raw materials across the country. Despite the ubiquity of air transport, most physical goods move by ground, as their value per unit weight does not justify air delivery (Research and Innovative Technology Administration Bureau of Transportation Statistics 2002). The primary commodity transported by river and rail in the U.S. is coal. Coal is an industrial and residential necessity, providing heat, electricity, and a means to produce steel. A disruption to this network could inflict costly consequences, as frustrated shipments attempt to find new delivery routes.

The Three Rivers region of Pittsburgh, Pennsylvania sits on one of the richest coal reserves in the U.S.. The Monongahela and Allegheny Rivers converge to form the Ohio River at the Point of Pittsburgh. These three rivers stretch more than 300 miles and define the area known as the Port of Pittsburgh. The United States Army Corps of Engineers (USACE) ranks the Port of Pittsburgh as the second busiest inland port in the United States (USACE 2012). The Port of Pittsburgh Commission (PPC) provides extensive information regarding locks, dams, and river characteristics (PPC 2012a). The Ohio River connects the Port of Pittsburgh to the rest of the Inland Waterways System, a system of more than 25,000 miles of navigable waters in the Eastern United States (Figure 1). Coal and other commodities are transported into and out of the region via barge on this river.

Figure 1. The Inland Waterway System. Source: PPC 2012b.

The Port of Pittsburgh is regulated by a series of locks and dams and provides the primary means of coal delivery to power companies and steel producers in the area. Labor disputes, natural disasters, terrorist attacks, and even anticipated maintenance on the existing infrastructure can disrupt the function of this system. A catastrophic disruption to the coal-delivery supply chain could cause national consequences, including a rise in utility costs and steel prices. The Port of Pittsburgh Commission reports that "inland waterway transportation is generally the least-costly transportation mode. Average cost ranges between $0.005 and $0.01 per ton-mile of cargo moved. This compares to nearly $0.05 for rail and $0.10 for truck" (PPC 2012b). Therefore, stakeholders are intent on providing resilient transportation along these waterways to maintain low costs.

The enormous capacity of the river system and its low operating costs make it the primary means of bulk commodity shipment through the Port of Pittsburgh. Although there are multiple modes of transport for coal in this region, the large demand volumes make it cost prohibitive to supply adequate quantities in the long term by means other than river. Figure 2 shows cargo capacity of different modes of transport; clearly barges can carry much more cargo.

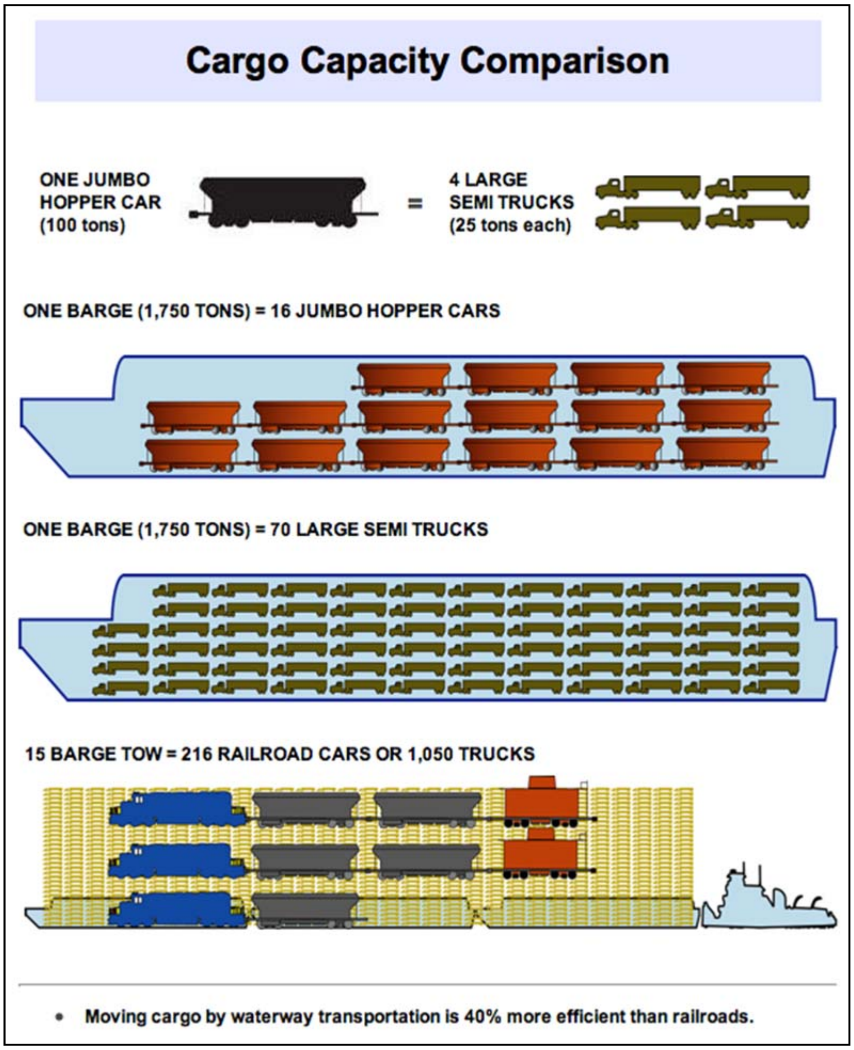

Figure 2. Comparison of cargo capacity of rail car, truck, and barge. Source: Port of Pittsburgh Commission, 2012c.

In practice, the most cost effective means for moving coal on the river is via multiple barges pushed by a single towboat. Figure 3 displays a "12-barge tow."

Figure 3. The most economical way to move coal is by barge. Source: USACE 2012.

The interdiction of coal delivery along these primary river-shipment routes would have dire implications. For purposes of this thesis, *interdiction* is the interruption of commodity movement through our system. Limited capacity and availability of rail cars calls into question the viability of trains. Additionally, transporting large volumes of coal via truck could place an extreme burden on the road network, causing immediate bottlenecks. Many coal consumers maintain some level of reserves on hand to mitigate fluctuations in delivery or consumption rates and for emergency situations. However, these reserves are finite, and steel manufacturers in the Pittsburgh region cannot run out of coal or they risk huge financial loses and catastrophic facility shutdowns.

The vulnerability of aging infrastructure along with economic significance makes Pittsburgh a real target. Protecting the city and its infrastructure is challenging—there are three modes of transportation and so many routes into the city that protecting them all is impossible. Potential attacks include blocking traffic through locks, destroying dams, dropping bridges that cross the rivers, or even attacking the commodity-carrying vessels. This infrastructure is not heavily guarded and is easily accessible. Protection of locks and dams from the shore is the responsibility of local municipalities, and defense from the water resides with the United States Coast Guard (USCG). Bridges and slow-moving vessels (barges travel at an average speed of approximately 4 miles per hour) are very accessible, making them soft targets. Repairs subsequent to an attack on this aging infrastructure are estimated to require weeks to months, depending on the extent of the damage and the components damaged.

The USCG is tasked with ensuring economic stability and safe navigation of these waterways. One of the missions of the USCG is the protection of Ports, Waterways, and Coastal Security (PWCS).

> PWCS is the protection of the U.S. Maritime Domain and the U.S. Marine Transportation System (MTS) and those who live, work or recreate near them; the prevention and disruption of terrorist attacks, sabotage, espionage, or subversive acts; and response to and recovery from those that do occur. Conducting PWCS deters terrorists from using or exploiting the MTS as a means for attacks on U.S. territory, population centers, vessels, critical infrastructure, and key resources. PWCS includes the employment of awareness activities; counterterrorism, antiterrorism, preparedness and response operations; and the establishment and oversight of a maritime security regime. PWCS also includes the national defense role of protecting military out-load operations. (USCG, 2011)

In Pittsburgh, the USCG District 8 Command has jurisdiction for these 328 miles of river, which connect Pennsylvania, Ohio, and West Virginia. Complicating the USCG mission are the many bridges, projected reductions in USCG force size, and increased concern about terrorist attack in the post-9/11 era. Traditional security is only part of the solution. This infrastructure faces not only deliberate threats from terrorists and saboteurs, but it is also at risk to disruptions from engineering failures, accidents, and natural disasters. As demand for coal increases, rising shipping traffic and strains on infrastructure will result. The USCG needs to be able to identify worst-case disruptions in advance of their occurrence and no matter their cause.

The solution to maintaining economic and industrial stability in the event of an attack is the development of a resilient system. For purposes of this thesis, we define *resilience* as the ability of a system to maintain its function in the presence of internal or external disruptions; this definition is consistent with that of the Homeland Security Advisory Council (HSAC 2006) and the Homeland Security Council (HSC 2007). Ways to achieve such resiliency include increased capacity of infrastructure, improved protection of critical components, or cost-effective re-routing plans to optimally ship commodities in the event of disruption. The U.S. National Strategy for Homeland Security says, “we must now focus on the resilience of the system as a whole—an approach that centers on investments that make the system better able to absorb the impact of an event without losing the capacity to function” (HSC 2007).

The goal of this thesis is to assess the resiliency of the system of rivers, rails, and roads that move coal from mines to customers in the Pittsburgh area. We use Defender-Attacker-Defender (DAD) techniques to identify which components to defend and provide minimum-cost solutions to routing in the event of failures in the system. By applying these methods to the Port of Pittsburgh, we assess the relative importance of critical system components in order to help the USCG identify where to focus its attention.

II. LITERATURE REVIEW

This thesis contributes to the body of existing works in the area of optimization, the defense of critical infrastructure, and the transportation of commodities. While the following related works are not exhaustive, they contain underpinnings vital to this work.

A. CRITICAL INFRASTRUCTURE AND RISK

The National Infrastructure Protection Plan (NIPP) identifies critical infrastructure as, "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, the national economy, national public health or safety, or any combination of those matters" (DHS 2009).

Risks to infrastructure threaten lives, economic stability, and national security. As defined in the DHS Risk Lexicon (DHS 2010), risk is "potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences." (In general, we follow definitions put forth in this Lexicon.) It is not enough to merely protect against initial attacks on critical infrastructure and key resources (CI/KR). As described in the NIPP, we must be prepared to (1) deter attacks, (2) endure their impact, and (3) regain normal operation as soon as possible (DHS 2009). The NIPP aims to deter, foil, or decrease the effects of purposeful attacks and to increase readiness, responsiveness, and resiliency of CI/KR in the event of an attack, natural disaster, or other emergency (DHS 2009). The NIPP promotes cooperation of private and government agencies in the development of prevention, response, mitigation, and recovery efforts. Providing security everywhere at all times is impossible with limited personnel, and building infrastructure that is completely resistant to attack is difficult with limited financial resources. This intentional defense guidance outlined in the NIPP fosters organizational cooperation to overcome inherent limits and achieve necessary readiness.

The Marine Transportation Security Act (MTSA) of 2002 mandates that vessels and ports conduct vulnerability assessments as part of local Area Maritime Security Plans (Maritime Transportation Security Act of 2002). The USCG Captain of the Port is the

Federal Maritime Security Coordinator charged with oversight of the local Area Maritime Security Committee, who develops and implements those plans.

Guided by the NIPP, DHS evaluates risk as a function of threats, vulnerabilities, and consequences and then applies this definition of risk to deliberate and non-deliberate events indiscriminately. The DHS has adopted Probabilistic Risk Assessment (PRA) to estimate risk and prepare for potential threats from both natural causes and malicious enemies (see Bedford and Cooke. 2001. for an introduction to PRA). In this context, *threat* is the probability of attack, *vulnerability* is the conditional probability of success given an attack, and *consequence* is the result of successful attack, measured either in lives lost or dollars damage (DHS 2009). Examples of this PRA application in use are the Risk Analysis and Management for Critical Asset Protection (RAMCAP) (ASME 2011), the Terrorism Risk Assessment and Management (TRAM) toolkit (NRC 2010), and the Maritime Security Risk Analysis Model (MSRAM), employed by the USCG (GAO 2010). Additionally, the DHS conducts data calls and information sharing to assess CI/KR and relies on the aggregate knowledge of its personnel to accurately assess vulnerability. By quantifying risk at each key component of a system, the goal of DHS is to allocate defense resources judiciously in order to mitigate risk. One example of these data-sharing efforts is the Constellation/Automated Critical Asset Management System (C/ACAMS, see DHS 2012 for details). This web-based tool allows users to access and share CI/KR information, assess vulnerabilities, and develop reaction plans. These types of information management and internal assessments, combined with probabilistic approach to attacks, drive DHS risk efforts and defense planning.

As documented by the National Research Council (NRC 2008, 2010) there are problems with these methods of evaluating risk. First, there is not enough historical data to assess probability of future terrorist attack, and it is questionable in this context whether past events are representative of future ones. Relying on subjective assessment from subject matter experts to assess probabilities has inherent biases and simply cannot be validated against ground truth. Second, deliberate attacks from an adversary are distinctly different from non-deliberate events, such as accidents, failures, or natural disasters, and should be handled separately. Acts of nature, for example, may be handled with a probabilistic approach, as these acts happen as random occurrences based on seasonal or climatic conditions, or on engineering failures or operational errors, and historical data is readily available for characterizing these probabilities. Even human errors or mishaps can be characterized by probabilities. But, once an intelligent adversary enters the scenario, the rules change (see Engel 2011 for a detailed discussion). This adversary has harmful motives and accomplishes his intent through thoughtful planning and observation of CI/KR. The actions of this attacker are not random, but deliberate. To assume that an adversary behaves according to known probabilities would be to neglect the autonomous nature of the enemy at our own peril.

Brown and Cox (2011) raise additional issues with predicting risk based on subjective probability estimates of possible enemy actions. Specifically, they contend that dismissing the differences between scenarios involving intelligent adversaries and random threats can have significant consequences. They argue that threat–vulnerability–consequence (TVC) formula *"Risk = (Probability of attack) × (Probability that attack succeeds, given that it occurs) × (Consequence of a successful attack)"* is a poor estimator of risk, amounting at best to a guess of potential risk. Additionally, they point out that PRA does not provide decision makers insight on where to invest resources to mitigate this risk and note that probabilities regarding enemy action may be impossible to correctly predict. Instead, they recommend focusing on enhanced infrastructure and defense efforts that improve the system's ability to rebound from an attack and quickly return to satisfactory operating conditions. Engel (2011) also summarizes some of the flaws of the threat-vulnerability-consequences approach to risk in the context of system interdiction models.

Brown and Cox (2011) suggest game theory as a superior approach to PRA when evaluating risk in a system. Game theory considers the intelligent decisions of both the attacker and the defender, allowing each to freely choose when, where, and how he acts, but admitting that defender acts will be visible to the attacker. This more closely represents an actual defender preparing for possible threats, an attacker seeking to inflict maximum harm, and a defender (or operator) attempting to manage his system in a damaged, degraded condition. Viewing the interaction between friendly and enemy combatants in this manner eliminates the requirement to subjectively identify consequences, vulnerabilities, and threats of a system and focuses attention on the CI/KR that, if attacked, would result in maximum frustration of the system.

The 2010 NRC review of DHS approaches to risk analysis concludes:

> Conclusion: These network disruption and systems resilience models (which supplant and move away from current limitations of *TVC* analyses for CI/KR) are ideal for longer-term investment decisions and capabilities planning to enhance infrastructure systems' resiliency, beyond just site-based protection. Such models have been used in other private sector and military applications to assist decision-makers in improving continuity of operations.
>
> Recommendation: DHS should continue to enhance CI/KR data collection efforts and processes and should rapidly begin developing and using emerging state-of-the art network and systems disruption resiliency models to understand and characterize vulnerability and consequences of infrastructure disruptions. (NRC 2010, page 69)

We follow this guidance to evaluate CI/KR resiliency on the Port of Pittsburgh.

There has been considerable interest in the use of game theory for security problems. Tambe et al. (2011) use game theory to consider security problems. They formulate a Stackelberg game for ports and inland waterway security in order to assist USCG efforts in combating terrorism. The Port Resilience Operational / Tactical Enforcement to Combat Terrorism (PROTECT) model is an example of the application of game theory techniques to defense efforts (Shieh et al., 2012). Additional applications of this technique include Assistant for Randomized Monitoring Over Routes (ARMOR) in the Los Angeles International Airport, Intelligent Randomization in Scheduling (IRIS) in the U.S. Federal Air Marshal Service, and Game Theoretic Unpredictable and Randomly Deployed Security (GUARDS) in the Transportation Security Agency (TEAMCORE 2011).

B. SYSTEM INTERDICTION MODELS

Another use of game theory has been to consider *system interdiction* problems. Wood (1993) introduces a deterministic interdiction scenario. He details the usefulness of this technique in the context of "reducing the flow of drugs and related chemicals through river and road networks in South America” (Wood 1993). His work considers two opponents, with a smuggler trying to maximize the amount of drugs transported through a network and an interdictor trying to minimize routes to achieve this objective. Wood uses a small 14-node, 25-arc sample problem to portray the interactions of the smuggler and interdictor on a capacitated network. He also considers the use of multiple commodities and other variations and extensions of this problem. Our problem is similar, with role reversals, where we are attempting to move coal across a network and the interdictor is an intelligent adversary, seeking to cut off our ability to traverse the system.

Brown et al. (2005, 2006) introduce *Defender-Attacker-Defender (DAD)* models to represent the interaction between an enemy (attacker) and an operator (defender). This three-move game begins with the defender analyzing his system and choosing a defense plan to minimize the effects of any potential attack. He may increase capacity, improve security, or reinforce vital system components. The next move belongs to the attacker, who evaluates the system, having full knowledge of the defender’s defense strategy and then attacks to inflict maximum damage. Finally, the operator attempts to manage the damaged system to minimize the impact of the attack. Wood (2011) provides a summary of network interdiction problems and the techniques for solving them.

Pidgeon (2008) develops a simulation model to estimate the costs associated with disruptions to the Marine Transportation System (MTS), specifically incidents at the major west coast ports of the U.S.. He explains the significance of western ports to the domestic economy, as these ports handle the majority of imported containerized cargo for the U.S.. He considers various scenarios, ranging from striking union workers to earthquakes in California that could cause delays in the handling of containerized cargo. Pidgeon considers the ability of government agencies to advise redirection of commercial vessels, assuming industry leaders would make wise, lowest-cost decisions in rerouting ships to alternate available ports. Pidgeon’s model uses queues to represent ships awaiting offload, and displays growing penalty costs related to infrastructure shortcomings. The model analyzes infrastructure capacity limitations and identifies choke points where government and/or commercial agencies may invest to mitigate penalty costs associated with delayed shipments.

Bencomo (2009) analyzes the impact of various disruptions on the containerized transportation system into and out of North America. He develops an Attacker-Defender (AD) model, looking first at the optimal routes of shipment, then considers the effects of an intelligent adversary, workforce strikes, and natural disasters. This model seeks the most efficient means to transport goods from source to destination by taking advantage of various modes of transport. He considers road, rail, and water travel and develops a model to appropriately choose the best mode of travel at different stages of delivery. The model seeks the most cost-efficient means to satisfy supplies and demands. He suggests that future areas of study investigate more accurate representations of transport systems. Additionally, he advocates for more involvement from key stakeholders, to better understand the true ramifications of disruptions on the system.

De la Cruz (2011) evaluates the ability of the MTS to import various goods into Hawaii, via refrigerated and non-refrigerated containers. He observes that the large majority of consumer goods come from outside the island. Due to the limited storage capacity of the island, the system is fragile and cannot easily handle disruptions, making it susceptible to attack. Using Attacker-Defender modeling, he identifies system components (e.g., piers, cranes, and terminals) that are vital to maintaining the uninterrupted flow of containerized shipments. His work assesses how well the Hawaiian MTS handles worst-case disruptions and the effect of those disruptions in terms of delivery shortages. By identifying key components of the system and analyzing the system's resiliency to attacks, de la Cruz affords government agencies and other commercial stakeholders insight into greatest areas of need for improved equipment, increased capacity, and better policies.

Babick (2009) challenges conventional risk management tools used by the Department of Homeland Security and compares current methods, such as RAMCAP, with AD and DAD algorithms. Babick demonstrates that DAD is superior to the risk-based techniques, consistently providing answers that are as good, or better. Additionally, he shows that results from the DAD model provide insight into necessary improvements to infrastructure, an advantage over the risk management methods. Focusing on the western U.S. rail network, Babick explains that DAD and AD produce optimal routes following an attack on the system. This exposes the susceptibility of certain arcs and nodes throughout the network and, as costs to redirect traffic rise, encourages further investigation of these critical pieces of infrastructure. This type of system transparency is not available in traditional PRA risk management methods.

Alderson et al. (2011) demonstrate the use of a Defender-Attacker-Defender (DAD) model in the context of a transportation system consisting of roads and bridges, and they provide a formal algorithm for solving the DAD tri-level optimization problem.

Engel (2011) compares risk-based assessment and game-theoretic techniques as viable USCG approaches to defending critical infrastructure against attack. The medium for this analytic comparison is the evaluation of the flow of coal along a particularly small portion of the Pittsburgh region. He develops an Attacker-Defender model, consisting of roads, railways, and rivers, to determine critical vulnerabilities to the shipment of a single commodity (coal) from mines to power plants and steel manufacturers. Using notional data, his analysis provides proof-of-concept about the potential insights from a more rigorous study.

C. CONTRIBUTIONS OF THIS THESIS

The primary contribution of this thesis is the development of an Operator’s Model that mimics the real-world behavior of coal transport in the Port of Pittsburgh and allows for systematic investigation of “what if” scenarios.

Building on the work done by Engel (2011), we expand the area of operation to include more mines and factories. We consider the movement of multiple types of coal, as contracted between individual suppliers and consumers. These changes add complexity, yet provide more realistic traffic flow, and a better understanding of the system in the Pittsburgh area.

We include multiple commodities, in the spirit of de la Cruz (2010), and multiple modes of transport as in Bencomo (2009). This produces a model that is closer to reality and provides further understanding of the interaction of these commodities on a complicated network.

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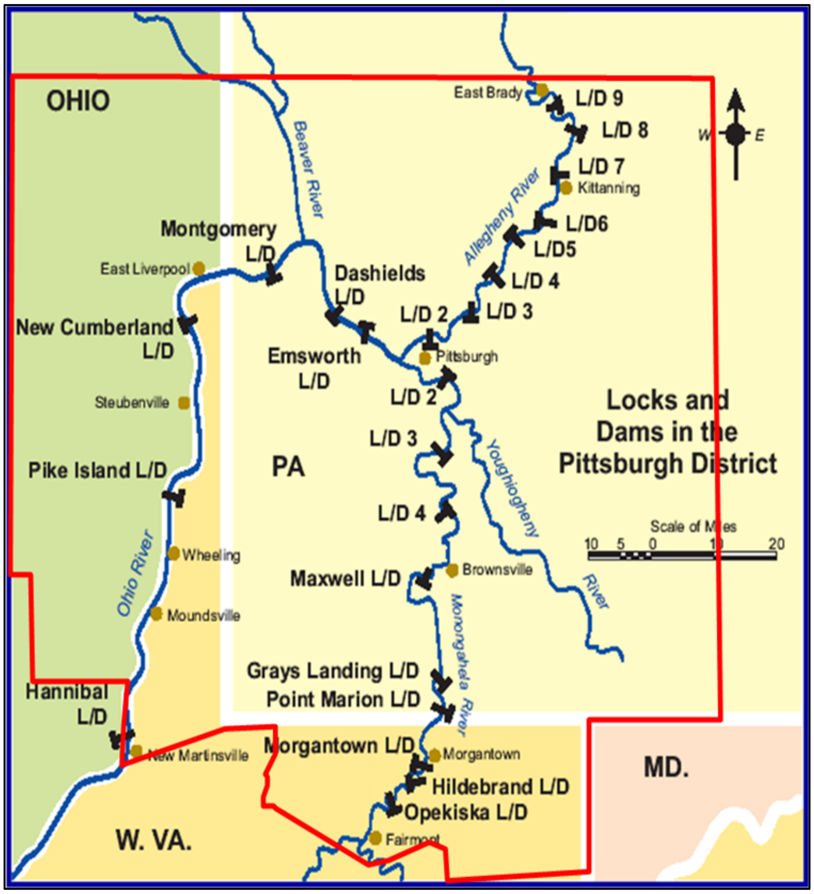
III. RIVER TRANSPORT

The starting point of any analysis of critical infrastructure is to understand its basic function and operations, so as to be able to assess the consequences of disruption to that function. River transportation is a primary means of moving large quantities of bulk commodities. Although rail lines and roads are important shipment modes, rivers garner special attention in this thesis. Because coal accounts for 76% of river traffic by volume through the Port of Pittsburgh (PPC 2010), we provide a more detailed description of river shipment

The Monongahela and Allegheny Rivers converge to form the Ohio River at the Point of Pittsburgh. Figure 4 depicts our area of interest (AOI) around Pittsburgh, including the many locks and dams. These three rivers stretch more than 300 miles and provide both public recreation and enormous commercial shipping capacity. These rivers also flow through the most extensive coal bed in the Appalachian Basin (Puglio 1983). Exploitation of coal in this region began as early as 1751 (White 1898). Companies in the area are faithful consumers of coal and many rely solely on this local commodity for producing steel and generating electricity.

The characteristics of coal vary regionally, and coal is rated on its burn quality. "Coal is classified into four main types, or ranks (anthracite, bituminous, sub-bituminous, and lignite), depending on the amounts and types of carbon it contains and on the amount of heat energy it can produce" (U.S. Energy Information Administration, 2012). Each coal consumer must balance costs, including delivery fees, with quality when purchasing contracts. This further complicates matters on the river, as consumers are not simply buying from the nearest mine, but rather buying the type of coal they need from the mine company that offers the best price. This results in non-obvious delivery routes, including many instances of coal being delivered to and from locations outside our AOI.



River Locks & Dams
Ohio River
Emsworth L/D
Dashields L/D
Montgomery L/D
New Cumberland L/D
Pike Island L/D
Hannibal L/D
Allegheny River
Allegheny L/D 2
C.W. Bill Young L/D 3
Allegheny L/D 4
Allegheny L/D 5
Monongahela River
Braddock L/D
Monongahela L/D 3
Monongahela L/D 4
Maxwell L/D
Grays Landing L/D
Point Marion L/D
Morgantown L/D

Figure 4. The Port of Pittsburgh consists of the Ohio, Monongahela, and Allegheny Rivers. This picture illustrates the location of various locks and dams (L/D) throughout our AOI, listed in the table to the right. Along the Ohio River our AOI is bounded by the Hannibal L/D. Along the Allegheny River our AOI is bounded by the Allegheny L/D 5. Along the Monongahela River our AOI is bounded by the Morgantown L/D. Source: USACE 2012.

Locks and dams make river travel possible. Dams maintain the water level, so large vessels can transit without running aground. The body of water between two dams is known as a *pool*. Dams create a tiered effect between pools throughout the river network. Figure 5 illustrates the sequences of pools on the Monongahela River upstream of and including Pittsburgh.

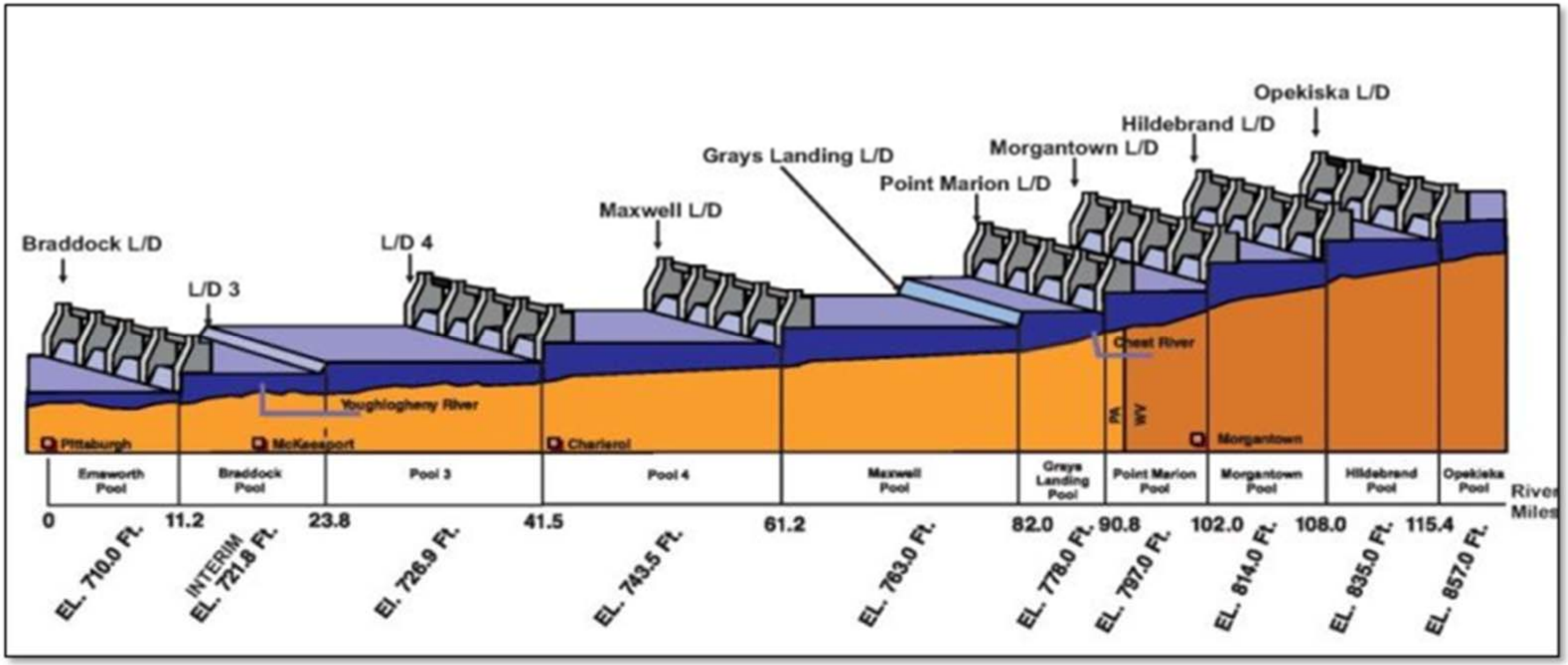


Figure 5. Dams and pools on the Monongahela River. Source: USACE 2012. The failure of the Monongahela L/D 4 results in the loss of navigatbility of the river segment or pool between the Monongahela L/D 4 and the Maxwell L/D. Such a failure implies the inability to transport coal via river to or from any facilities (i.e., mines or plants) located within that pool.

Locks enable vessels to transition from one pool to the next (Figure 6). Passing through a lock, known as "locking-through," can take 30 minutes to several hours, depending on queuing, number of barges, and the number of parallel locks available for use.

Figure 6. Aerial view of Emsworth Lock and Dam, Pittsburgh, PA. There are two parallel locks (at right) that allow passage between the pools of water separated by the dam (at left). Source: USACE 2012.

The USACE has responsibility for the continued operation of these waterways. In total, the USACE operates and maintains 12,000 miles of commercial inland navigation channels, including dredging riverbeds and repairing the 600 dams under its responsibility (USACE 2012). Because of aging infrastructure throughout the river system, scheduled maintenance on locks and dams creates delays of weeks to months. These planned repairs are announced to the public far in advance. The USCG also uses their website to notify the public of delays, blockages, and expected river conditions in nearly real-time. The average age of the 192 inland waterway locks is 50 years old (Gillis 2009). In the event of catastrophic damage, the USACE relies heavily on established contractor support. Pursuant to the National Response Framework (DHS 2008), the USACE assists DHS with engineering support and construction supervision, handling significant debris removal and demolition when the situation is unmanageable at the local or state level. The Monongahela River has two of the oldest locks maintained by the

USACE, built in 1905 and 1907. In Calendar Year 2009 together they locked 10,602 vessels carrying 26,044,941 tons of cargo (USACE 2012). Sudden loss of a dam would have cascading affects, damaging infrastructure downstream.

Disruptions along the waterways range from mere inconveniences, such as minor maintenance, to long-term outages resulting from dam failure. This range of possibilities carries varying consequences, including increased costs to operate the system. These incremental cost increases are clearly undesirable. In September of 2009, Michael Hennessy, Vice President of river operations for CONSOL Energy, said, "A catastrophic breakdown of one of the Monongahela river's aging locks, namely the 100-year-old Lock 3, would bring hundreds of thousands of tons of barge traffic to an abrupt halt with little opportunity to quickly or efficiently divert the cargo to other land-based transport modes" (Gillis 2009).

Natural disruptions along the river may result from flooding, freezing, infrastructure failure, or large debris (i.e., a sunken vessel). Some delays are scheduled, while others are unanticipated and result from seasonality or random happenings. Maintenance downtime can last from weeks to months, but auxiliary locks, and small temporary locks used to mitigate complete stoppage, alleviate some of the backlog of barges. The need for unscheduled maintenance increases as critical components fail from years of use.

Another class of disruption includes deliberate attacks from a malicious agent. These types of attacks may include destroying critical infrastructure (e.g., locks, dams, or bridges) and are more challenging to prepare for. A May 2012 attempt to attack nearby infrastructure using "explosive materials to damage physical property affecting interstate commerce," is a real-world example of such an attempt at disruption (Barrett 2012).

Figure 7 shows that delays have increased over time as a result of scheduled and nonscheduled maintenance.

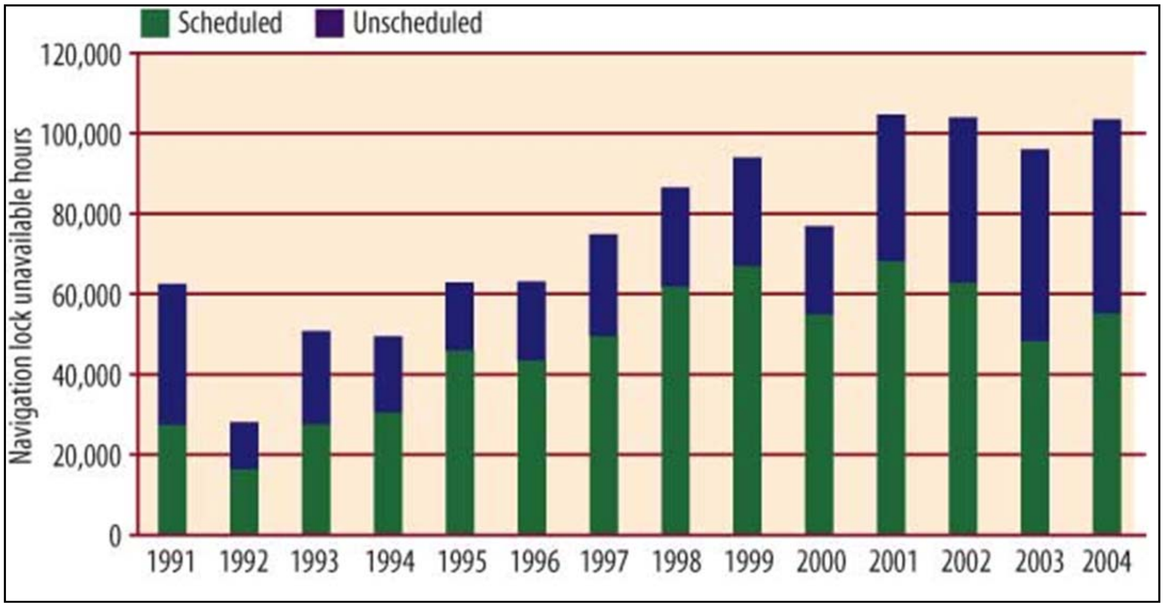


Figure 7. Unscheduled lock outages. Source: Smith (Coal Power Magazine), 2007.

The fragility of this shipping network and the limited resources of the USCG and USACE make the Port of Pittsburgh vulnerable to long-term disruption. Applying game theory system interdiction techniques to this problem will pinpoint CI/KR components whose loss has the biggest impact on system function. This proactive approach will identify vulnerabilities in the context of a malicious adversary and will aid decision makers as they prepare for worst-case scenarios and defend critical lines of commerce.

IV. THE OPERATOR'S MODEL

The transport of coal through Pittsburgh is driven by contracts between suppliers and consumers. These shipping contracts are satisfied through the movement of coal by barge, train, and truck from mines to customer destinations within our AOI. These contracts link the delivery of a specific commodity from a specific supplier to a specific consumer at a specific time.

We model a multi-commodity transshipment system in which each commodity (i.e., each individual contract) can travel along multiple modes of transport, each having different capacity and cost. We consider two types of coal (bituminous and lignite) and keep track of contracted shipments by destination (customer) and week of delivery. Thus, a "commodity" in this model is in fact a combination of (coal type, source, destination, and delivery week).

We partition the set of nodes into two types. "Terminal" nodes are the origins and destinations of flow, they can store commodity inventory, and they are not associated with any particular mode of transportation. A terminal is a place where coal is supplied, consumed, and/or stored or a place where coal is transferred on or off one of the three modes of transport. In contrast, each "transshipment" node is associated with a specific mode of transportation, and it cannot originate, terminate, or store commodities.

Accordingly, there are two types of arcs. "Transfer arcs" move commodity between terminal nodes and transshipment nodes. "Transshipment arcs" move commodity between transshipment nodes. Commodities can move from one mode of transportation to another only by transiting through a terminal node. Additionally, modes of shipment have finite capacities with varying costs. Cranes, conveyors, excavators, and other innovative means accomplish loading and offloading. These arcs have both a capacity (i.e., equipment limitations) and cost (loading cost of $0.15 per ton and offloading cost of $0.30 per ton). The drawing in Figure 8 illustrates the relationship terminal nodes have with modal (i.e., river, rail, or road) transshipment nodes, enabled by intermodal transfer arcs.

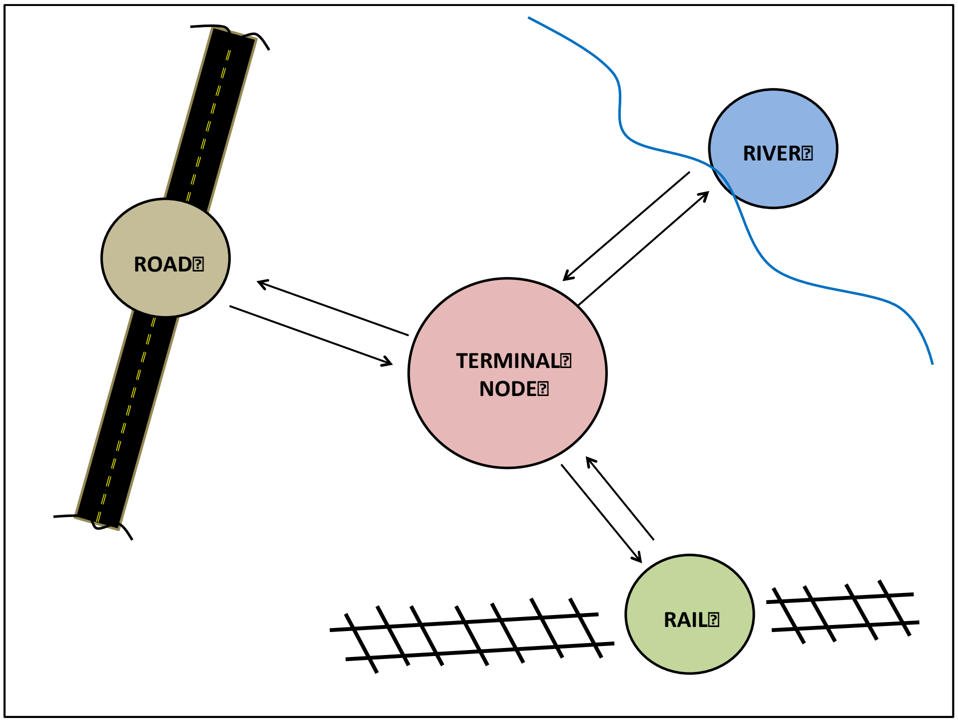


Figure 8. Transfer arcs between a terminal node and transshipment nodes for each of the three modes of transportation considered in this thesis. Capacities on transfer arcs may limit the ability to move coal to or from an individual mode of transportation.

We consider the movement of coal over a time horizon ranging from one to several weeks. The only interaction between time periods is through commodity inventory that is carried from one time period to the next at a terminal node.

To understand how the system functions in the presence of disruptions, we must first understand how the system functions under normal operations. We begin with the assumption that all coal is transported via river during standard operating conditions.

A. MODEL FORMULATION

We present the formal mathematical model of system operations, in Naval Postgraduate School standard form (amended 27 July 2012).

Index Sets [~cardinality]:

$n \in N$	nodes [~100]
$r \in R \subseteq N$	transshipment nodes (alias *i*, *j*)
$d \in D \subseteq N$	terminal nodes (alias *o*,*s*) $R \cap D = \varnothing$; $R \cup D = N$
$m \in M$	modes of transport; M={river, rail, road, transfer}
$mx \in MX = M \setminus \text{'transfer'}$	
$\{m,i,j\} \in A \subseteq M \times N \times N$	directed arcs (from node i to node j using mode m) [~500]
$\{m,i,j\} \in U \mid \{m,i,j\} \in A \vee \{m,j,i\} \in A$	undirected arcs [~250]
$w \in W$	time periods (alias *wd*) [weeks, ~50]
$\{w,wd\} \in FORE\_LOG$	time periods *w* during which shipments can be made for contracts due in time period *wd* ($w \leq wd$)[~50]
$\{m,i,j,w\} \in ARC\_I$	if arc $\{m,i,j\}$ is damaged, it is still inoperable during time period w [~500]
$c \in C$	cargo type [~2]
$\{c,d,wd\} \in COM$	contract commodity [~1,000]

Input Data [units]:

$contract_{o,c,d,wd}$	amount of cargo type *c* originating at node *o* contracted for delivery to node *d* during time period *wd* [tons]
$cost_{m,i,j}$	cost per unit flow for using arc $\{m,i,j\} \in A$ [cost]
$cpen_{o,c,d,wd}$	per-unit penalty for failing to deliver contract volume [cost/ton]
$hcost_s$	holding cost for inventory at terminal *s* [cost/ton]
inv_cap_s	inventory capacity at terminal *s* [tons]

$spen_{s,c}$ per-unit demand shortfall penalty at node s of cargo type c [cost/ton]

$\overline{ATTACK}_{m,i,j}$ binary indicator as to whether arc $\{m,i,j\} \in A$ is damaged; = 1 if arc $\{m,i,j\}$ is damaged, = 0 otherwise [binary]

$q_{m,i,j}$ per unit flow penalty for using arc $\{m,i,j\} \in A$ if damaged [cost]

$cap_{m,i,j}$ directed capacity of arc $\{m,i,j\} \in A$ [tons]

$ucap_{m,i,j}$ undirected (shared) capacity of arcs $\{m,i,j\} \in A$ and $\{m,j,i\} \in A$, $i < j$ [tons]

Computed Data:

$demand_{c,d,wd}$ demand for cargo type c at node d at during time period wd [tons]

$$demand_{c,d,wd} = \sum_{o \in N} contract_{o,c,d,wd}$$

Non-negative Decision Variables [units]:

$F_{o,w,c,d,wd}$ flow from mine o during time period w of contract cargo $\{c,d,wd\}$ [tons]

$Y_{m,i,j,w,c.d,wd}$ flow along arc $\{m,i,j\} \in A$ during time period w of contract cargo $\{c,d,wd\}$ [tons]

$IN_{s,w,c,d,wd}$ inventory at node s at start of time period w of contract cargo $\{c,d,wd\}$ [tons]

$A_{s,w,c,d,wd}$ transfer node s shortage at start of time period w of contract cargo $\{c,d,wd\}$ [tons]

$R_{s,w,c,d,wd}$ transfer node s excess at start of time period w of contract cargo $\{c,d,wd\}$ [tons]

Formulation 1: Defender Model (D)

$$\min_{F,Y,IN,A,R} \sum_{\{m,i,j\}\in A, w\in W} \left[cost_{m,i,j} + q_{m,i,j}\left(\overline{ATTACK}_{m,i,j}\big|_{\{m,i,j,w\}\in ARC\_I} + \overline{ATTACK}_{m,j,i}\big|_{\{m,j,i,w\}\in ARC\_I}\right)\right] \sum_{\{c,d,wd\}\in COM, \{w,wd\}\in FORE\_LOG} Y_{m,i,j,w,c,d,wd}$$

$$+ \sum_{o\in D, \{c,d,wd\}\in COM} cpen_{o,c,d,wd}\left(contract_{o,c,d,wd} - \sum_{\{w,wd\}\in FORE\_LOG} F_{o,w,c,d,wd}\right)$$

$$+ \sum_{s\in D, \{c,d,wd\}\in COM, \{w,wd\}\in FORE\_LOG} hcost_s IN_{s,w,c.d.wd}$$

$$+ \sum_{s\in D, \{c,d,wd\}\in COM, \{w,wd\}\in FORE\_LOG} spen_{s,d} A_{s,w,c,d,dw} + \sum_{s\in D, \{c,d,wd\}\in COM, \{w,wd\}\in FORE\_LOG} spen_{s,d} R_{s,w,c,d,dw} \qquad \text{(S0)}$$

s.t.

$$\sum_{\{w,wd\}\in FORE\_LOG} F_{o,w,c,d,wd} = contract_{o,c,d,wd} \qquad \forall o\in D, \{c,d,wd\}\in COM \qquad \text{(S1)}$$

$$-F_{s,w,c,d,wd} \quad -IN_{s,w,c,d,wd}$$
$$- \sum_{\{'transfer',d,s\}\in A} Y_{'transfer',d,s,w,c,d,wd} + \sum_{\{'transfer',s,d\}\in A} Y_{'transfer',s,d,w,c,d,wd}$$
$$+IN_{s,w+1,c,d,wd}\big|_{\{w+1,wd\}\in FORE\_LOG}$$
$$+A_{s,w,c,d,wd} - R_{s,w,c,d,wd} = -demand_{c,d,wd}\big|_{d=s\wedge w=wd} \qquad \forall s\in D,$$
$$mx\in MX, \{w,wd\}\in FORE\_LOG,$$
$$\{c,d,wd\}\in COM \qquad \text{(S2)}$$

$$- \sum_{\{mx,i,o\}\in A} Y_{mx,i,o,w,c,d,wd} + \sum_{\{mx,o,j\}\in A} Y_{mx,o,j,w,c,d,wd}$$
$$- \sum_{\{'transfer',s,o\}\in A} Y_{'transfer',s,o,w,c,d,wd} + \sum_{\{'transfer',o,s\}\in A} Y_{'transfer',o,s,w,c,d,wd}$$
$$= 0 \qquad \forall mx\in MX, o\in D,$$
$$w\in W, \{w,wd\}\in FORE\_LOG,$$
$$\{c,d,wd\}\in COM \qquad \text{(S3)}$$

$$\sum_{\{c,d,wd\}\in COM, \{w,wd\}\in FORE\_LOG} Y_{m,i,j,w,c,d,wd} \le cap_{m,i,j} \qquad \forall (m,i,j)\in A, \forall w\in W \qquad \text{(S4)}$$

$$\sum_{\{w,wd\}\in FORE\_LOG, \{c,d,wd\}\in COM} \left(Y_{m,i,j,w,c,d,wd}\big|_{\{m,i,j\}\in A}\right.$$
$$\left. + Y_{m,j,i,w,c,d,wd}\big|_{\{m,j,i\}\in A}\right) \le ucap_{m,i,j} \qquad \forall \{m,i,j\}\in U, \forall w\in W \qquad \text{(S5)}$$

$$\sum_{\{c,d,wd\}\in COM} IN_{s,w,c,d,wd} \le cap\_inv_s \qquad \forall s\in D, w\in W \qquad \text{(S6)}$$

The objective (S0) measures the total transit, transfer and inventory holding cost, plus any penalties for shortfalls or contract violations. The “attack” terms will be discussed in a following section, but here merely represent arcs whose costs have risen so dramatically they will not be used. Each constraint (S1) ensures for some contract that total flows from the source mine meet the contract amount. Note that in case of anticipated disruptions, flows may leave the mine earlier than the delivery contract week to be stored in intermediate inventory somewhere and conveyed to the customer later. Each constraint (S2) accounts for balance of flow at some transfer node at the start of a planning period for some commodity. Each constraint (S3) accounts for inter-modal transfers at some terminal node of come commodity, including inventory, shortfall, supply, and demand. Constraints (S4) and (S5) enforce directed and undirected capacity on arcs, respectively. Each constraint (S6) limits inventory held at some terminal at the start of some planning period.

This model finds the minimum cost means of delivering the contracted amount from each source to each destination, along one of several modes of transport, each having their own costs and capacities. An interdiction on an arc increases its usage cost, so if there is a disruption in one system (e.g., river), then the model looks for a low-cost alternative route (e.g., river, rail, or road). There is a penalty ($cpen_{cod}$) for violating delivery of contracted amounts (e.g., by satisfying a customer from an alternative supplier), but in general this penalty is less than the penalty for incurring a customer shortfall ($spen_{sc}$).

The model has the flexibility to move and store coal in advance of its contract delivery date. This is advantageous when planning for scheduled maintenance or when buffering inventories to reduce the impact of unplanned disruptions. This functionality is controlled by the *FORE_LOG* mechanism in the formulation, which maintains an aspect of realism in delivery planning by limiting the model’s forecasting ability. A reasonable use of this mechanism might be to allow the model to plan ahead and move coal up to four weeks in advance. This prevents the model from transporting all coal in the first week of operations, limited only by infrastructure capacity. This unrestricted movement of coal is inconsistent with industry practice, which is more similar to a Just-In-Time system.

This thesis only uses a single time period of one week, a restriction that could be used to considerably simplify the model exposition. However, we have chosen to display the full model for a multi-time period planning horizon and show how shipments can preposition contracts and how demand can be satisfied before anticipated future losses of system components.

B. BUILDING THE NETWORK

In this section, we describe how we use information about the real system to develop data that we can use as input to the Operator Model formulation. The goal is to have our mathematical model mimic real-world behavior.

Dams separate rivers into pools, enabling navigability. Locks allow movement from one pool to the next. Figure 9 illustrates this concept of segmenting rivers and provides a numbering system throughout the Port of Pittsburgh.

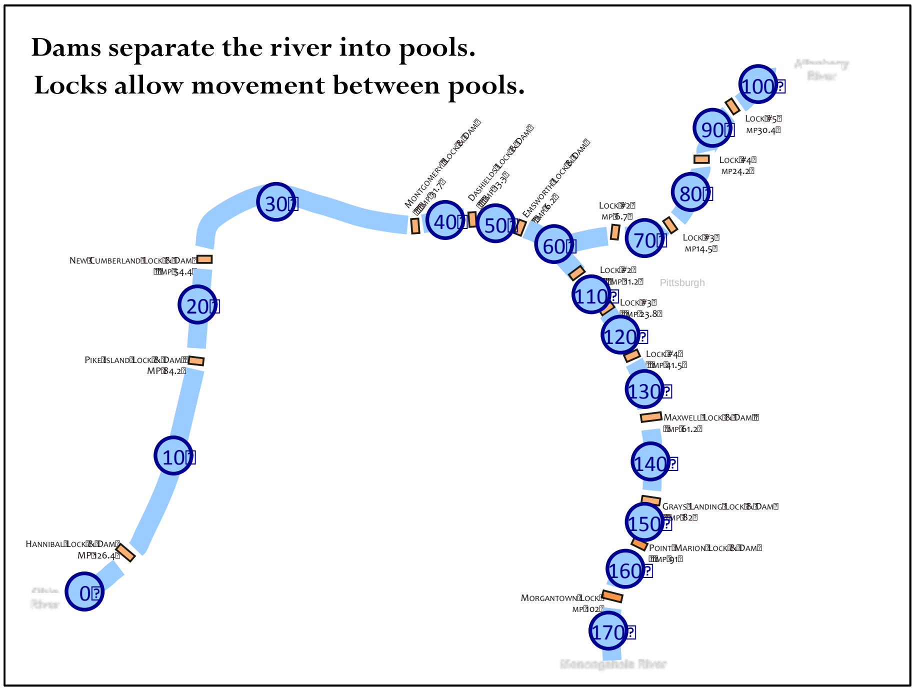


Figure 9. Dams segment the river into pools, which are numbered. Locks enable transit between pools. The Hannibal L/D and the Pike Island L/D on the Ohio River form Pool 10.

Our numbering scheme for locations is as follows. Starting at the downstream end of the AOI, we assign each river pool an increasing multiple of 10. We assign each river terminal associated with that pool a number equal to the pool plus a value 1–9 representing its relative geographic location within the pool. The result is that the locations are naturally sorted (from downstream to upstream) according to their identification numbers (low to high). The simplified river network in Figure 10 illustrates the use of the pool identification numbering convention and the relationship terminals share in a pool.

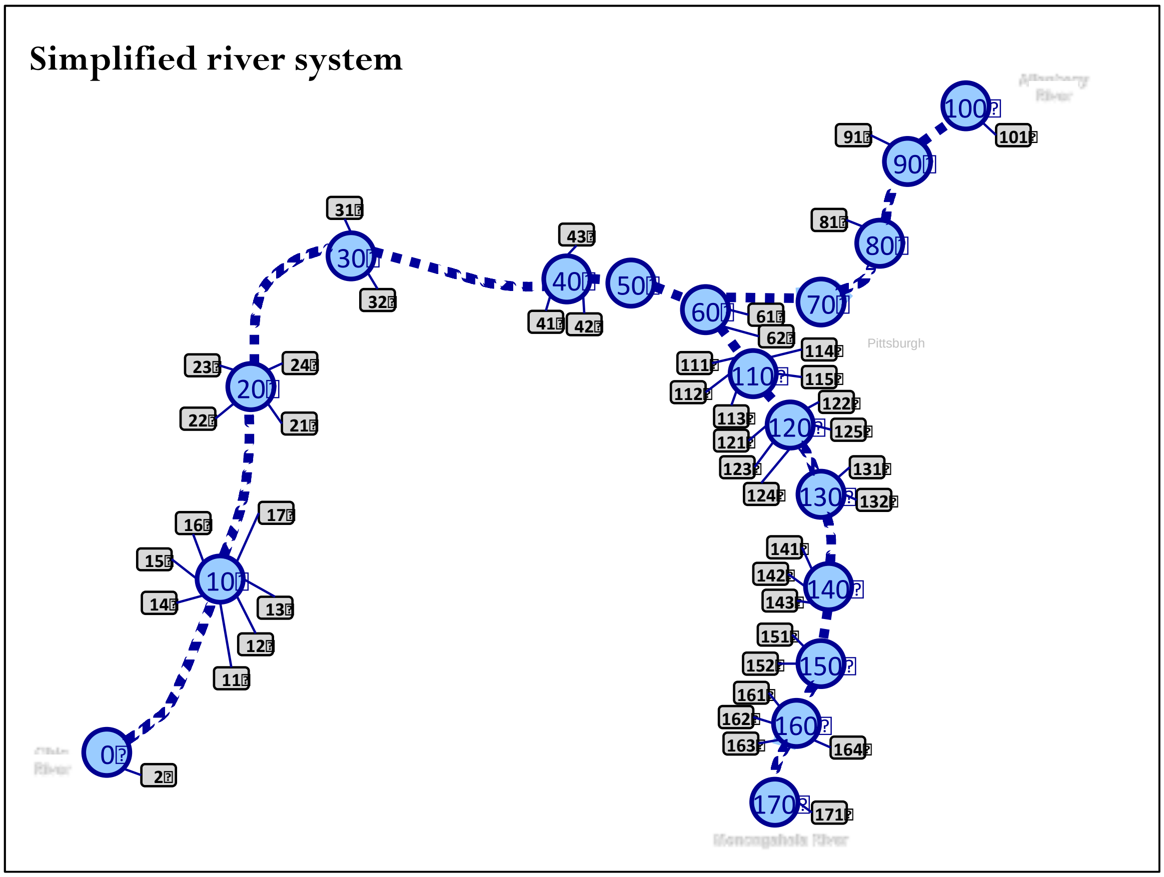


Figure 10. Simplified river system showing a total of 44 terminals connected to 18 pools. Terminal 16 is located in Pool 10.

Terminals also connect to the rail and road network in a similar manner. Figure 11 shows the rail and road networks, including illustrative bridges that cross rivers and connect land masses.

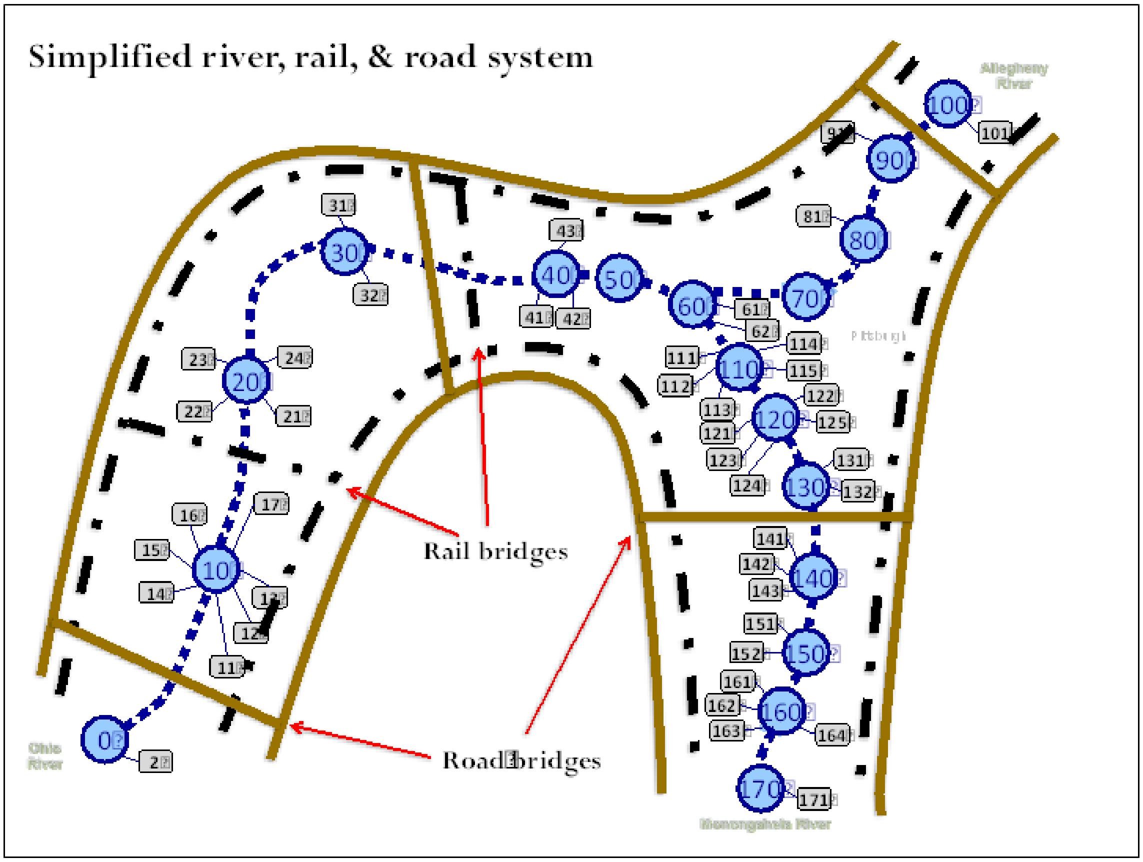


Figure 11. Simplified river, rail, and road system, with bridges connecting landmasses by crossing over rivers.

This overall network has several different kinds of arcs that play specific roles in our analysis.

- *Transfer arcs from terminal nodes to and from transshipment nodes* represent the ability to move commodity on or off a particular mode of transport. The capacities of these arcs are constrained by the physical equipment and/or processes available for loading and unloading coal. An interdiction on a transfer arc means that the terminal cannot send or receive coal from that transport mode.
- *Arcs connecting pools* represent the ability to move commodity through the locks separating the pools. An interdiction on such an arc results in the inability to move commodity between pools.

- *Arcs representing commodity movement within a pool.* In order to represent an attack on a dam that could result in the loss of an entire river pool, we "split" each pool node into an "inbound" and "outbound" node and connect these with a single directed arc (see Ahuja, Magnanti and Orlin 1993, p. 41–42 for a discussion of this "node splitting" technique). An interdiction on this single arc results in the inability to move commodity within the pool.

- *Arcs representing movement on rail or road segments.* Bridges, in particular, can form bottlenecks that constrain movement on land; interdictions on these arcs represent restrictions of such movement.

Each of the arcs in our network has an associated cost and capacity, which are important factors in how the Operator's Model chooses to route commodity flow.

C. CAPACITY AND COST

1. Capacity of Rivers

For the purposes of our analysis, we assume a river has limitless capacity. Barges travel at a speed of roughly 4 miles per hour and are restricted to the geographical contours of the river. However, navigating a lock limits throughput. Barges can carry 1,500 tons of cargo. A standard barge *tow* consists of 12 to 15 barges tied together (National Waterways Foundation 2008). A standard barge tow can take from two to eight hours to pass through a lock (Waterways Council 2011). Assuming 24 hours of operation per day and 7 days of operation per week, we have a capacity of (*15 barges per barge tow x 1,500 tons per barge x 8 barge-tows per hour x 24 hours per day x 7 days per week* =) 30.24 million tons per week.

The costs of transporting commodities by river are less than other modes of travel. The Port of Pittsburgh Commission states the average cost per ton-mile by barge is between \$0.005 and \$0.01 (PPC 2012b). For the purpose of this analysis, we will use a cost per ton-mile of \$0.008.

2. Capacity of Rail (Including a Discussion on Bridges)

A jumbo hopper rail car can carry approximately 100 tons of cargo. Coal train length, measured by the number of railcars coupled together, is limited by the number of engines employed, steepness of track grades, Department of Transportation (DOT) regulations (DOT 2012), and other mechanically limiting factors such as air-brake restrictions. A typical coal train can safely pull 150 fully loaded coal hoppers. Each coal train then carries (*100 tons of cargo per hopper x 150 fully loaded hoppers per train =*) 15,000 tons.

Like locks on a river, bridges can create bottlenecks for rail traffic, as only a finite number of trains can traverse the bridge during a given time epoch. A 2006 survey established there are 446 bridges within the Pittsburgh city limits, the most of any city in the world, surpassing Venice, Italy (Regan 2006). A train of 150 cars is (*46 feet long per hopper car x 150 hopper cars =*) 7,000 feet long (Environmodal 2012). At a safe speed of 15 miles per hour (Norfolk Southern Railroad Company 2012), including stops, (*15 mph / 7,000ft =*) 11.3 trains per hour could pass a given point. This speed includes loading, offloading, stops, and operational time. Operating 24 hours per day and 7 days per week results in a maximum capacity of (*11.3 trains per hour x 24 hours per day x 7 days per week =*) 1,898 trains, with a total cargo capacity of (*1,898 trains x 15,000 tons per train =*) 28.5 million tons per week.

Additional capacity limitations include the number of rail lines and the availability of rail cars and engines. Trains are constrained to tracks. While this might seem restrictive, it does provide more route diversity than barges constrained to rivers.

The average cost to move coal by rail car is $0.05 per ton-mile (PPC 2012b).

3. Capacity of Roads (Including Bridges)

A conservative estimate of the maximum capacity of a coal-carrying truck is 25 tons (The Energy Library 2009). Trucks provide the most flexibility of any mode of transportation. Trucks are typically employed only for short movements as the costs to move such small volume quickly erase potential profits.

Again, bridges create bottlenecks and limit total throughput. There are a total of 75 road bridges within our AOI that cross the Ohio, Monongahela, and Allegheny rivers. The average weekly traffic over some of Pittsburgh's busiest bridges in 2009 was around 20,000 vehicles per day (less than 10% or 2,000 were trucks) (City-Data 2012). Assuming anything greater than a 50% increase in traffic would halt movement, we take 30,000 (*20,000 + .50 x 20,000*) as the maximum capacity of any bridge during a day. This represents a 500% increase in truck traffic, which would be significant, but necessary for emergency rerouting. The 10,000 trucks equates to (*10,000 vehicles per day x 7 days per week x 25 tons per truck =*) 1.75 million tons of coal per week by road.

Transporting coal by trucks on roads is the most expensive option at $0.10 per ton-mile (PPC 2012b).

4. Capacity of Terminals

Terminals are locations with the capacity to load and/or offload cargo or to transfer commodities from one mode of shipment to another. Each terminal is unique and may possess different kinds of heavy lifting equipment (e.g., conveyors, electric whirler cranes, hoists, or clamshell buckets). The availability of commodity-transferring assets presents capacity limitations at each terminal. Transfer capacity may vary by mode of transport.

Additionally, some terminals are not accessible by every mode of transportation. For instance, some terminals do not have rail lines or have limited road access.

The speed of commodity transfers also presents capacity limitations. Offloading and loading does not happen instantaneously. Large shipments of coal, up to 15 barges each carrying 1,500 tons of coal, take time and manpower to move. Each piece of commodity-moving equipment operates at a different speed and some terminals are not outfitted with the newest technology or the fastest equipment.

For the purposes of our analysis, we assume the average cost for loading coal onto barges, rail cars, or trucks is $0.15 per ton. Because offloading is more labor intensive and costs are higher, we assume the cost of this is $0.30 per ton.

D. INVENTORY

In our Operator's Model, any terminal node can carry inventory to facilitate low-cost transport of coal. In practice, however, power plants typically carry a certain amount of inventory, on average 45 days, in order to compensate for interruptions in supply such as miner's strikes and/or holidays, adverse weather or transportation problems (Phillips 2008). Methods of storage are closed silos and open storage.

E. REPAIR TIMES

When a piece of infrastructure is damaged, whether by deliberate or non-deliberate means, it is not necessarily lost forever. Repairs to river, rail, or road infrastructure take time, but are often joint efforts by government and non-government agencies. For the purposes of our analysis, repair times for critical infrastructure are measured in weeks. We simplistically assume that transfer equipment (i.e., conveyors or cranes) take two weeks to repair. Locks are uniquely constructed and repairs are labor-intensive tasks that we assume take four weeks each. Dams are the most time-consuming repairs, assumed here to take 13 weeks each. Roads and rail lines are typically repaired within one week; therefore we consider their repair times to be negligible, as these repairs can be accomplished within a single model time period.

F. TRAFFIC DEMAND BY ORIGIN-DESTINATION

The U.S. Army Corps of Engineers (USACE) maintains lock throughput data for the entire inland waterways. Our study considers 2009 data for the Port of Pittsburgh. This data contains the following noteworthy fields of information:

- Commodity Name,
- Origin Name,
- Destination Name,
- Delivery Date, and
- Tons.

Working with the USCG, USACE provided a comma-separated-value (csv) file with over 20,000 lines of data representing individual movements of coal. Given this extremely valuable source of information, we face two challenges. First, we need to understand whether these historical coal flows have structure that could perhaps provide insight into the most critical parts of the river. Second, we need to get the data in a form that can be used by our mathematical AD model, which we implemented in the Generalized Algebraic Modeling System (GAMS) (GAMS 2012). To address these challenges, we use Visual Basic for Applications (VBA) in Microsoft Excel (Microsoft Corporation 2012) to manipulate, sort, filter, and aggregate the data. This section describes this data development and its insights.

1. Data Preprocessing

Our raw data includes numerous commodities, such as grain, gravel, and petroleum-based products, but the data also includes lignite coal and bituminous (a.k.a. coke) coal. Coal is of sole importance to this study. Because we focus exclusively on coal movement, we filter out non-coal goods, leaving around 15,000 lines of data.

Next, we transform the data into a form that follows a standard naming convention and adheres to the requirements for use in GAMS (e.g., use of underscore characters instead of spaces). We reduce commodity names to simply COAL_A or COAL_B. We assign each origin and destination location a unique identification number as a programing simplification and in order not to reveal sensitive data that exposes specific customer relationships. Additionally, we associate each location with a specific river pool so we can easily observe relationships along the waterways. Finally, we associate each delivery date with a week of year (1 through 52). The result is a new augmented table with the following fields:

- New Commodity Name,
- New Origin Name,
- Origin ID,
- Origin Pool,
- New Destination Name,
- Destination ID,
- Destination Pool, and
- Week Number.

Table 1 shows a partial list (Monongahela River terminals only) of our terminal names with their identification numbers. Because our river network connects to a much larger network of rivers via the Ohio River, we adopt the convention of a notional node outside of our region. This single ‘super’ terminal, known as the OHIO_1, represents an aggregate of all source and destination terminals outside of our AOI.

TERMINAL NODE	NODE ID #
OHIO_1	1
MON_1	111
MON_2	112
MON_3	113
MON_4	114
MON_5	115
MON_6	121
MON_7	122
MON_8	123
MON_9	124
MON_10	125
MON_11	131
MON_12	132
MON_13	141
MON_14	142
MON_15	143
MON_16	151
MON_17	152
MON_18	161
MON_19	162
MON_20	163
MON_21	164
MON_22	171

Table 1. Terminal nodes with node identification numbers. Our Ohio Super terminal is OHIO_1 and its node identification number is 1. The last terminal on the Monongahela is MON_22 and its node identification number is 171.

Additional nodes enable the model to properly replicate real-world functionality, such as an offloading point along a river. These include river nodes, rail nodes, and road nodes. There are many of these nodes in our model; several examples of these nodes are listed in Table 2.

Intermodal Nodes	Node ID #
ROAD_OHIO_1	342
ROAD_MON_1	343
ROAD_MON_2	344
…	
RAIL_OHIO_1	242
RAIL_MON_1	243
RAIL_MON_2	244
…	
RIVER_OHIO_1	139
RIVER_MON_1	140
RIVER_MON_2	141

Table 2. River, rail, and road nodes facilitate intermodal transfers. The ROAD_OHIO_1 node is the road node associated with the OHIO_1 terminal and its node identification number is 342.

Arcs connecting these nodes are limited by capacities related to their mode of transport (i.e., river, rail, or road) and loading and offloading equipment (cranes, conveyors) at terminals

2. Data Aggregation

Observing coal throughput is a first step in understanding key infrastructure. Trying to understand thousands of pieces of data independently is a daunting task, so we build an origin-destination matrix to group similar data and expose delivery patterns. The matrix in Figure 12 illustrates this aggregation of coal data. The row and column headers are our terminal nodes, listed by their identification numbers. Lines in the matrix represent locks and dams. Flows are grey-scale coded to highlight supply and demand fluctuations, with light grey representing low, dark grey representing medium and black representing high tonnage.

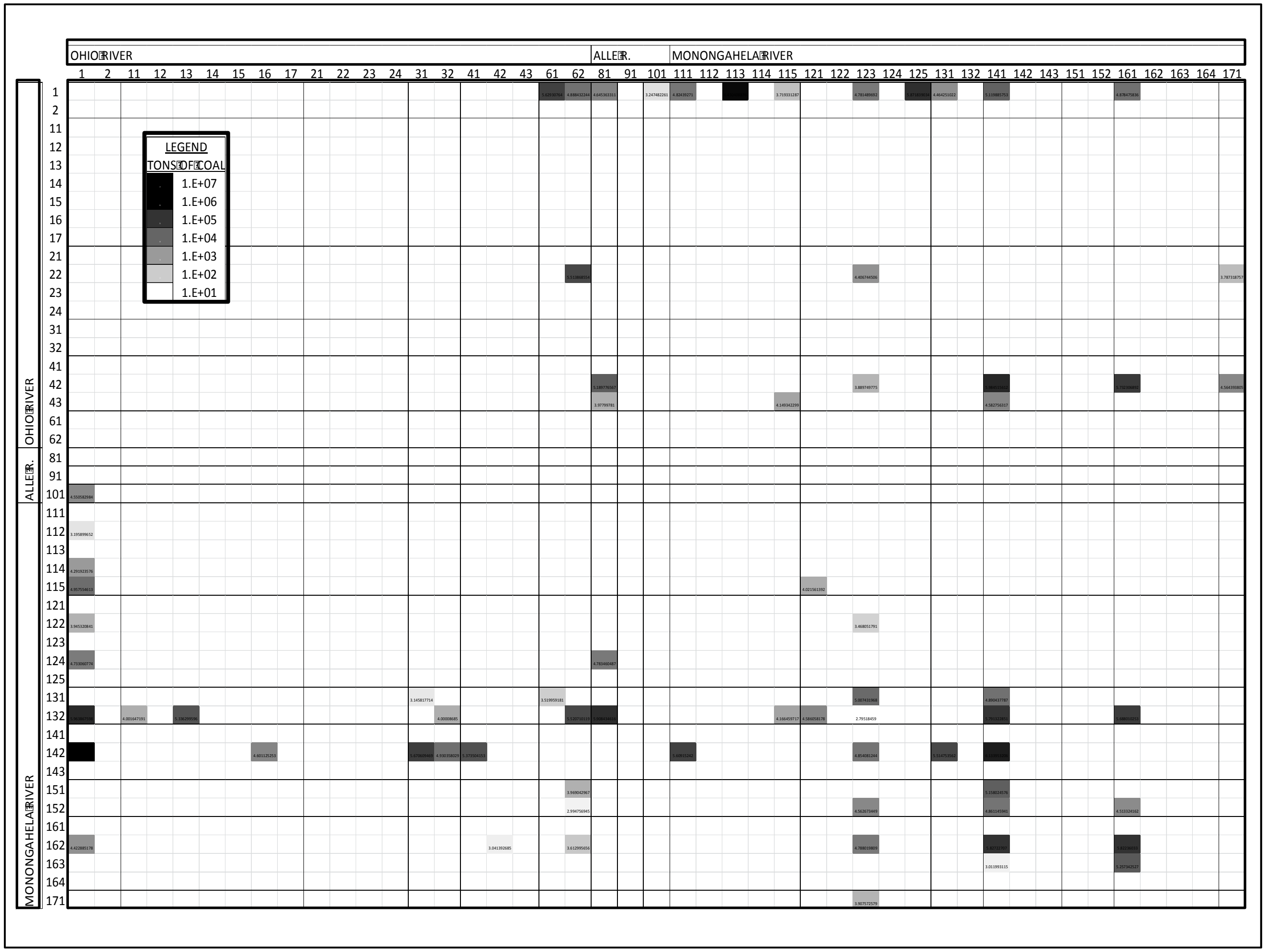


Figure 12. Origin-Destination Matrix for coal transport. The sparsity of this matrix indicates that in practice there are only a relatively small number of contracted supplier-customer relationships.

From this matrix we develop Table 3 that shows a ranking of the most significant shippers and receivers of coal for an entire year. Clearly, coal moving to and from OHIO_1 is significant. But, flow along the Monongahela is also very substantial.

RANK	TONS	RECEIVED	% OF TOTAL		RANK	TONS	SHIPPED	% OF TOTAL
1	4,788,373	OHIO_1	25.27%		1	6,627,767	MON_15	34.97%
2	4,081,834	MON_14	21.54%		2	4,356,684	OHIO_1	22.99%
3	2,694,070	MON_4	14.22%		3	3,458,572	MON_13	18.25%
4	1,980,786	MON_19	10.45%		4	1,704,103	OHIO_17	8.99%
5	1,079,146	ALLY_1	5.69%		5	1,429,133	MON_20	7.54%
6	749,909	MON_1	3.96%		6	358,129	OHIO_11	1.89%
7	744,456	MON_11	3.93%		7	184,139	MON_12	0.97%
8	473,327	MON_2	2.50%		8	181,888	MON_21	0.96%
9	469,791	OHIO_14	2.48%		9	153,200	MON_17	0.81%
10	429,211	OHIO_19	2.26%		10	142,763	MON_18	0.75%
11	376,478	MON_9	1.99%		11	114,821	MON_10	0.61%
12	356,279	MON_12	1.88%		12	101,198	MON_6	0.53%
13	236,322	OHIO_16	1.25%		13	61,871	OHIO_18	0.33%
14	216,920	OHIO_5	1.14%		14	35,529	ALLY_3	0.19%
15	95,186	OHIO_15	0.50%		15	19,585	MON_5	0.10%
16	49,062	MON_7	0.26%		16	11,755	MON_8	0.06%
17	42,805	MON_23	0.23%		17	8,083	MON_23	0.04%
18	39,914	OHIO_8	0.21%		18	1,570	MON_3	0.01%
19	34,015	MON_6	0.18%					
20	10,038	OHIO_3	0.05%					
21	1,768	ALLY_3	0.01%					
22	1,100	OHIO_17	0.01%					

Table 3. Top receiving and shipping terminals in the entire Port of Pittsburgh. The OHIO_1 terminal is essentially an exit portal from our AOI. Note the large amounts of coal entering and leaving the system at this terminal.

Figure 13 illustrates how seasonal climate changes affect coal demand in the Pittsburgh region. Cold winter months (December, January, February, and March) and hot summer months (July and August) increase heating and cooling needs. The lowest consumption occurs in October (~7.6 million tons), compared to the highest consumption in February (~12.6 million tons). February has shorter days, approximately 10.5 hours of sunlight, meaning more electricity is used for lighting, compared to 12 hours of sunlight in October. Colder February temperatures, on average 35 degrees Fahrenheit, result in increased heating costs compared to mild October temperatures of 55 degrees Fahrenheit (The Weather Channel 2012). These seasonal factors influence a nearly 66% increase in coal consumption. In order to observe model behavior under a more stressful coal delivery scenario, we consider normal operation during one of these peak periods, specifically week 1.

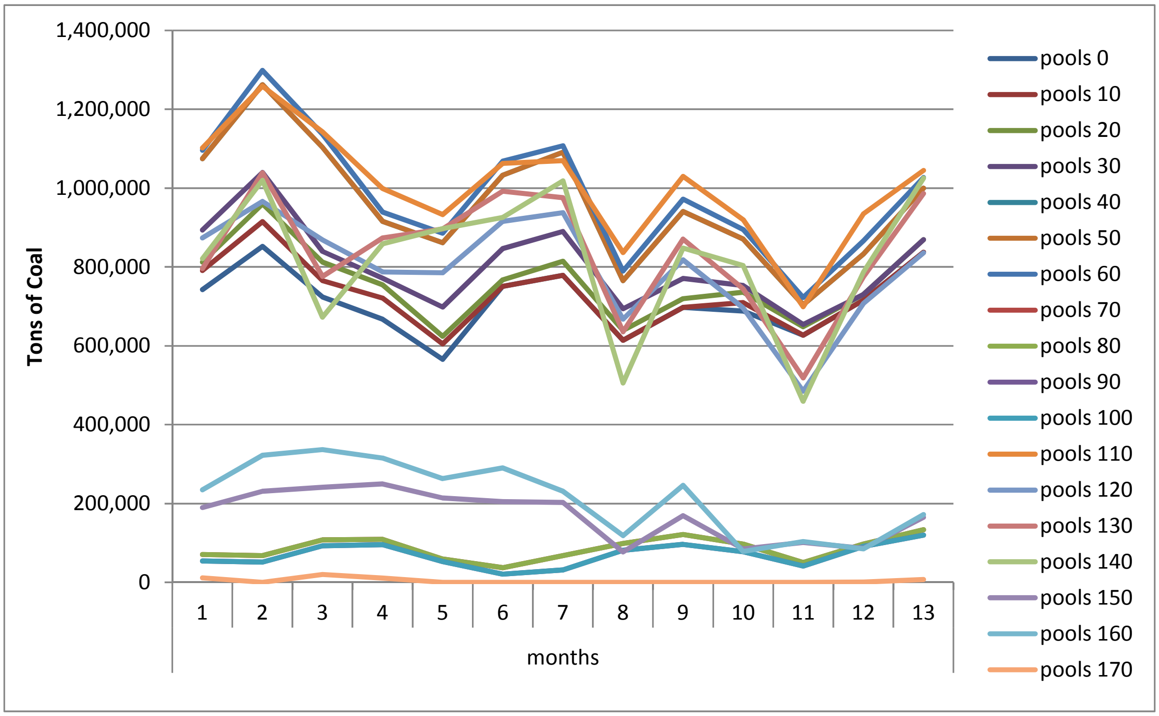


Figure 13. Coal flows through the Pittsburgh AOI by four-week "month." Seasonal fluctuations are mostly consistent across pools, with the first eight weeks of the calendar year showing the largest overall flows.

As one would expect, locks and dams conveying large volumes of coal are more significant to the system than those locks and dams supporting little or no coal movement. Because dams maintain navigability along the river, it is vital that we understand which dams support the most coal traffic. Figure 14 shows coal throughput, measured in tons, for each pool in the Port of Pittsburgh. It is clear that pools 40, 50, 60, and 110 constitute a top-tier. The next significant group consists of pools 0, 10, 20, 30, 120, 130, 140 and possibly 150 and 160. Finally, it seems that pools 70, 80, 90, 100, and 170 are less critical to the movement of the majority of coal through our AOI. This cursory analysis helps to develop our intuition regarding coal traffic and provides a baseline understanding of standard coal operations in the Pittsburgh region.

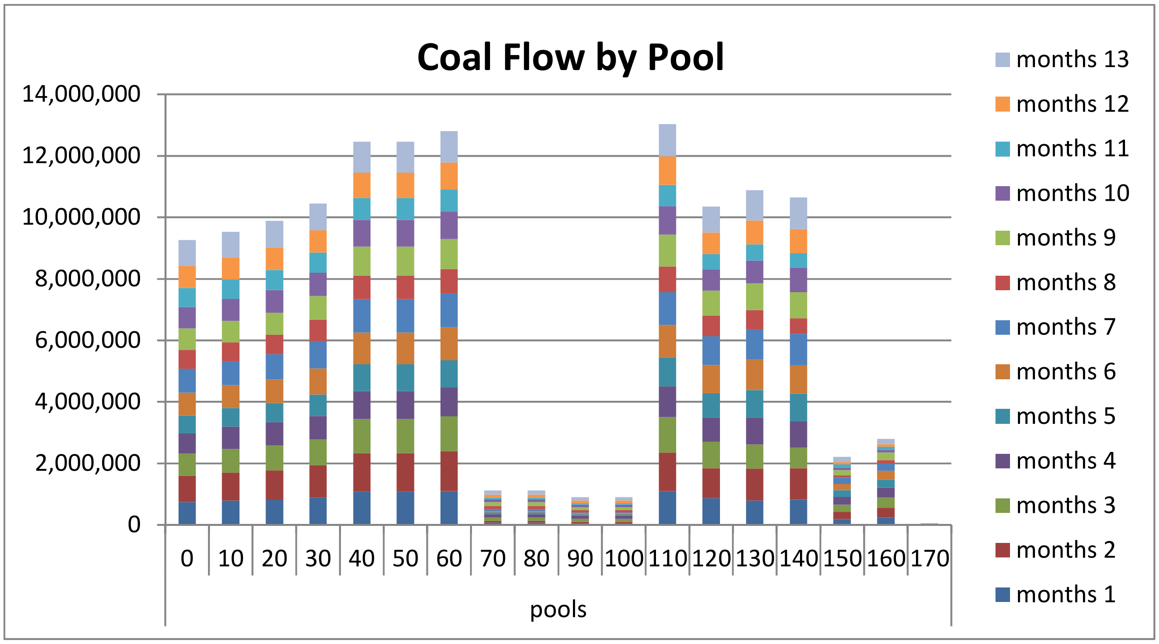


Figure 14. Coal flow through each pool in the Pittsburgh area. Pools 0 through 60 constitute the Ohio River. Pools 70 through 100 constitute the Allegheny River. Pools 110 through 170 constitute the Monongahela River.

The bar chart in Figure 14 illustrates the disproportionately small volume of coal flowing through the Allegheny River (Pools 70, 80, 90, and 100). This chart also shows the large amount of coal flowing into, out of, and remaining on the Monongahela River (Pools 110 through 170). For these reasons, we focus our attention on the Monongahela River.

G. BUILDING INPUT FILES FOR GAMS

Constructing usable input files for GAMS requires the thoughtful collection and aggregation of various data fields. Figure 15 displays a portion of the *arc_data.csv* file, which lists all arcs by mode, source, and destination. The data file also includes directed and undirected capacities (*cap* and u*cap*), cost per ton-mile to traverse the arc (*cost*), a penalty value for attempting to traverse the arc if the arc is attacked (*q*), and a repair time (*recon_time*) for each arc. This file is an example of the types of files necessary for system interdiction modeling with GAMS. Such files consist of thousands of lines of information, which are impractical to manually generate. The use of explicit rules and programming logic applied via VBA coding enables quick, accurate computation and provides flexibility for later changes.

	A	B	C	D	E	F	G	H
1	mode	source	destination	cap	cost	q	ucap	recon_time
2	RAIL	RAIL_MON_3	RAIL_MON_BRIDGE_1	28500000	1.35	10000	28500000	1
3	RAIL	RAIL_MON_3	RAIL_MON_BRIDGE_2	28500000	1.32	10000	28500000	1
4	RAIL	RAIL_MON_3	RAIL_MON_BRIDGE_3	28500000	1.34	10000	28500000	1
5	RAIL	RAIL_MON_3	RAIL_MON_BRIDGE_4	28500000	1.41	10000	28500000	1
6	ROAD	ROAD_MON_3	ROAD_MON_2	1750000	0.78	10000	1750000	1
7	ROAD	ROAD_MON_3	ROAD_MON_4	1750000	0.87	10000	1750000	1
8	ROAD	ROAD_MON_3	ROAD_MON_5	1750000	0.74	10000	1750000	1
9	ROAD	ROAD_MON_3	ROAD_MON_6	1750000	0.65	10000	1750000	1
10	ROAD	ROAD_MON_3	ROAD_MON_7	1750000	0.71	10000	1750000	1
11	RIVER	RIVER_MON_3	POOL_120_IN	30200000	0.005	10000	30200000	2

Figure 15. The *arc_data.csv* file showcases various fields necessary for system interdiction modeling. Generating such files manually is impractical. The RAIL arc originating from RAIL_MON_3 and destined for RAIL_MON_BRIDGE_1 has a directed capacity (*cap*) and undirected capacity (*ucap*) of 28,500,000, a transportation cost of $1.35 per ton-mile, an interdiction penalty (*q*) of 10,000 and a repair time (*recon_time*) of 1 week.

Time developing data is time well spent, even if the upfront cost to evaluate raw data may seem high. Our raw data contains over 20,000 lines of information with over 25 unique fields. However, the reward for properly assessing the data and digesting the story the numbers tell is worth the investment. This initial analysis enables quick understanding of coal movement through the AOI, gives us some cursory intuition regarding the more significant and less significant infrastructure components, and provides useful input for GAMS to quickly solve large, complex problems.

H. ASSESSING BASELINE OPERATIONS: THE MONONGAHELA RIVER

In the remainder of this thesis, we focus on the flow of coal on the Monongahela River. Although only a subset of our entire AOI, it is a region with perhaps the highest density of river terminals. Figure 16(Left) identifies this narrowed AOI.

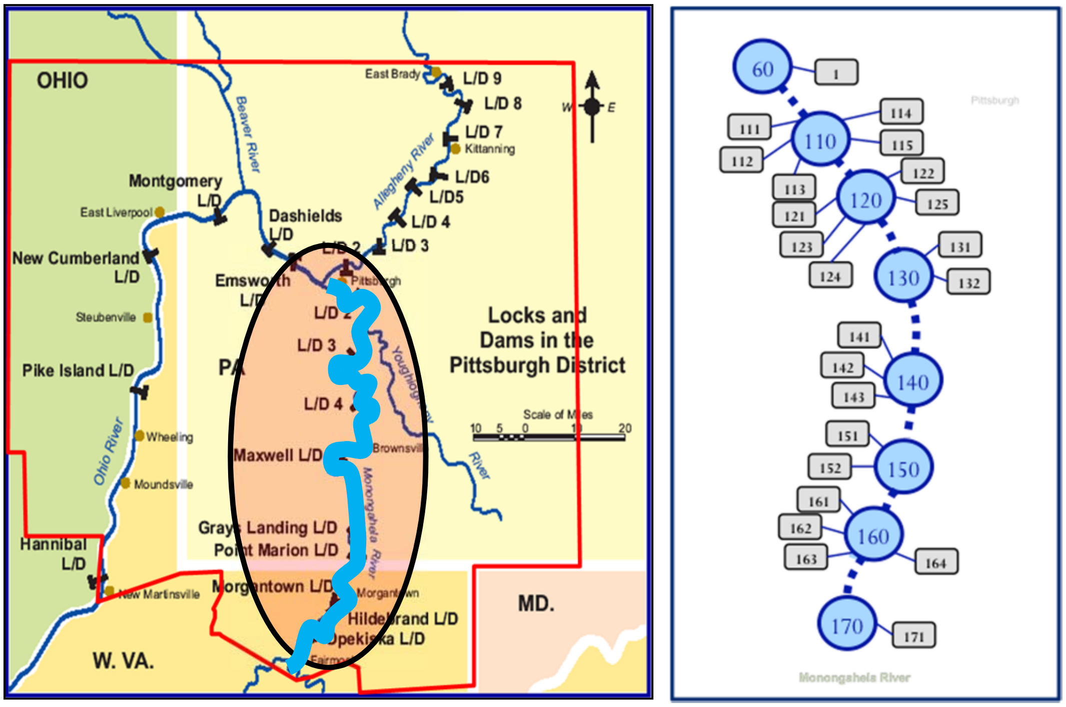


Figure 16. Left: The Monongahela River highlighted in blue within the oval. Right: Network representation of the Monongahela River.

To further make the case for the significance of focusing on the Monongahela River, the largest coking plant in the U.S., the U.S. Steel Clairton Plant, and the largest underground coal mine in the U.S. both reside on this river (Waterways Council 2010). Additionally, the river has 24 terminals, eight pools, seven locks and dams, eight rail bridges, and 26 road bridges. Although reduced in size, this system has significant "internal" coal flow (i.e., shipments originating from a terminal on the Monongahela River and destined for delivery to another terminal on the Monongahela River), as well as significant inbound and outbound coal shipments (i.e., coming to or from terminals on the Ohio River). Figure 16(Right) illustrates our narrowed focus of the Monongahela River network.

Having developed the necessary input data for the Operator's Model, we begin with an analysis of uninterrupted operations. Considering only one week of operations, our model estimates 1,244,879 tons of coal is delivered at a cost of $255,450. All coal is transported along the river and transfer costs account for approximately one-third of total cost. This requires a minimum of 711 fully loaded barges.

These operating costs serve as a baseline for all subsequent analysis. With no interdictions the Operator's Model finds the least costly method of transporting all shipments of coal from source to destination. In this case, the mode of RIVER is chosen for its low cost per ton-mile rate. This is consistent with the real system, in which all commodities move by barge.

In reality, contracts between suppliers (e.g., mines) and consumers (e.g., electricity plants) drive flows from sources to destinations. Table 4 displays contract data for the first week of operation on the Monongahela River. Keep in mind that Ohio super terminal OHIO_1 represents source and destination activity outside of our narrowed AOI, which only includes the Monongahela River.

CONTRACTS				
SOURCE	**DESTINATION**	**CARGO TYPE**	**WEEK**	**AMOUNT**
OHIO_1	OHIO_1	COAL_A	1	6957
OHIO_1	MON_6	COAL_A	1	3097
OHIO_1	MON_4	COAL_A	1	22165
OHIO_1	MON_11	COAL_A	1	2236
OHIO_1	MON_14	COAL_A	1	9775
OHIO_1	MON_19	COAL_A	1	9802
MON_5	OHIO_1	COAL_A	1	1431
MON_8	MON_9	COAL_A	1	988
MON_12	MON_9	COAL_A	1	1171
MON_13	OHIO_1	COAL_A	1	14780
MON_13	MON_14	COAL_A	1	2131
MON_13	MON_19	COAL_A	1	2088
MON_15	OHIO_1	COAL_A	1	59788
MON_15	MON_14	COAL_A	1	15059
MON_20	MON_9	COAL_A	1	2952
MON_20	MON_14	COAL_A	1	5003
MON_20	MON_19	COAL_A	1	7609

Table 4. Week 1 contracts between mines and plants. The contract between MON_15 and OHIO_1 is for cargo type COAL_A, in week 1, for 59,788 tons.

To explain in more detail the commodity flows in our model, we will focus on the 59,788 tons of COAL_A transported from MON_15 (Node ID #143) to OHIO_1 (Node ID #1). The cartoon depiction in Figure 17 demonstrates movement of coal from the MON_15 source node to the OHIO_1 destination node. The coal passes through several locks and dams; as the total tonnage is far less than the maximum capacity for a lock during a one-week period. Also, note the transfers from MON_15 onto the river and ultimately off the river to OHIO_1. The total cost for the delivery of this coal is $27,383, which is a function of distance, mode of travel rate (recall, river = $0.008 per ton mile, rail = $0.05 per ton mile, road = $0.10 per ton mile), total tonnage, plus loading and offloading costs (loading = $0.15 per ton and offloading = $0.30 per ton).

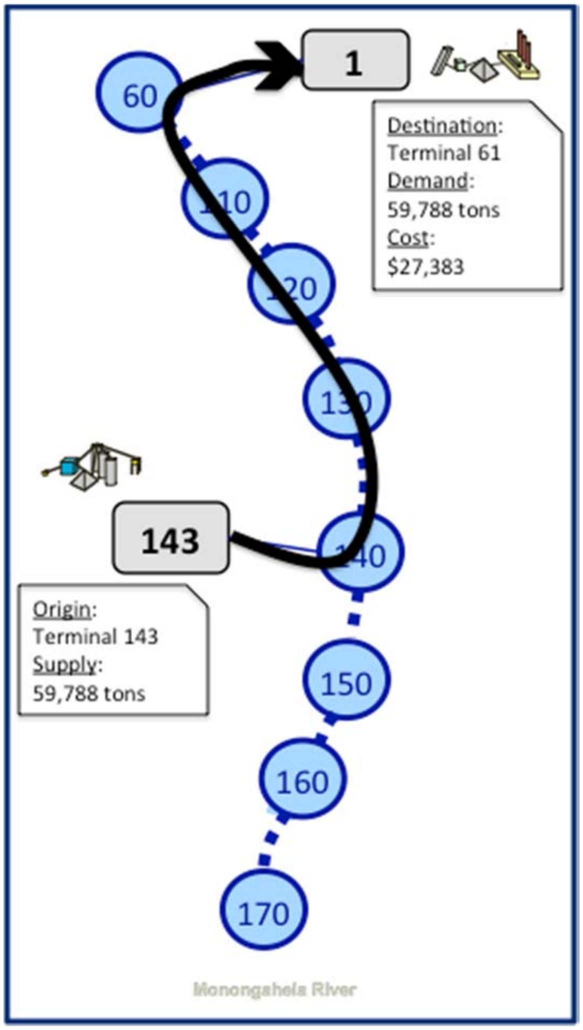


Figure 17. The flow of coal satisfying the contract from the MON_15 mine at terminal node #143 to the OHIO_1 plant at terminal node #1.

V. ATTACK AND DEFENSE OF RIVER OPERATIONS

Attacks to river infrastructure in the Port of Pittsburgh pose considerable threat. In a single week, the Monongahela River moves more than one million tons of coal at a cost of more than $250,000. In this chapter, we identify interdictions that result in worst-case disruptions, where "worst-case" means the highest total cost even after the system has rebalanced flows.

We use our Operator's Model as a starting point. In the event of an attack, the Operator's Model will reroute cargo, finding the cheapest means to satisfy demand in a disrupted environment. Undisrupted, the system loads cargo on the river, the cargo travels to its destination, and the cargo is offloaded. A disruption to the river unavoidably increases traffic on other modes of transport. Because river transport is the cheapest mode of travel, moving cargo by rail or road certainly increases cost. This increase in traffic may also challenge shipment capacities (e.g., insufficient number of available trucks or rail cars) or exceed transfer equipment capacities (e.g., slow conveyors or small cranes); further increasing costs if demand is frustrated.

In our analysis, we first consider the effects of a single attack: analyzing the attacker's most impactful single-attack locations and ranking them accordingly. Then we consider multiple simultaneous attacks, where the attacker chooses the most impactful locations to for two, three, four, and five simultaneous attacks. We compare these outcomes in an operator's "resiliency curve." Finally, we consider attacks under varying conditions: first, perfectly protected dams and, then, perfectly protected locks and dams. These two alternative scenarios provide insight on where and/or how best to employ limited resources to improve system resiliency to disruption.

A. ATTACKER'S MODEL

The Attacker's Model follows directly from the Operator's Model formulation, by replacing the input data $\overline{ATTACK}_{mij}$ with a decision variable X_{mij}.

Additional Data

num_attacks	Number of allowable attacks

Additional Variables

X_{mij}	Disrupt Flow on arc *(m,i,j)*, binary indicator as to whether arc $(m,i,j) \in A$ is damaged; = 1 if arc (*m*,*i*,*j*) is damaged, = 0 otherwise

Formulation 2: Attacker-Defender Model (AD)

$$\max_{X} \min_{\substack{F,Y,IN,\\A,R}} \sum_{\substack{\{m,i,j\}\in A,\\ w\in W}} \left[cost_{m,i,j} + q_{m,i,j} (X_{m,i,j} |_{\{m,i,j,w\}\in ARC\_I} + X_{m,j,i} |_{\{m,j,i,w\}\in ARC\_I}) \right]$$

$$\sum_{\substack{\{c,d,wd\}\in COM,\\ \{w,wd\}\in FORE\_LOG}} Y_{m,i,j,w,c,d,wd}$$

$$+ \sum_{\substack{o\in D,\\ \{c,d,wd\}\in COM}} cpen_{c,o,d} (contract_{o,c,d,wd} - \sum_{\{w,wd\}\in FORE\_LOG} F_{o,w,c,d,wd})$$

$$+ \sum_{\substack{s\in D,\\ \{c,d,wd\}\in COM,\\ \{w,wd\}\in FORE\_LOG}} hcost_s IN_{s,w,c.d.wd}$$

$$+ \sum_{\substack{s\in D,\\ \{c,d,wd\}\in COM,\\ \{w,wd\}\in FORE\_LOG}} spen_{s,c} A_{s,w,c,d,dw}$$

$$+ \sum_{\substack{s\in D,\\ \{c,d,wd\}\in COM,\\ \{w,wd\}\in FORE\_LOG}} spen_{s,c} R_{s,w,c,d,dw} \qquad \text{(A0)}$$

s.t. $\quad$ (S1), (S2), (S3), (S4), (S5)

$$X_{mij} = X_{mji} \qquad \forall (m,i,j) \in A \qquad \text{(A6)}$$

$$\sum_{(m,i,j)\in A} X_{mij} \le 2 \times num\_attacks \qquad \text{(A7)}$$

$$X_{mij} \in \{0,1\} \qquad \forall (m,i,j) \in A \qquad \text{(A8)}$$

The objective function (A0) replaces (S0) and now takes a bi-level max-min form, with decision variables X_{mij} replacing data $\overline{ATTACK}_{mij}$. Operating constraints (S1)-(S5) apply as before. Constraints (A6) make sure that any attack on a directed arc also affects its symmetric arc. Constraints (A7) enforce the attacker's "budget." Constraints (A8) enforce the binary nature of attacks.

We implement the Attacker's Model using the General Algebraic Modeling System (GAMS 2012), and solve it with Bender's Decomposition (see Wood. 2011. for details on the use of this technique to solve bi-level network interdiction problems) using the CPLEX Optimization Solver (ILOG 2012).

B. WORST-CASE SINGLE ATTACK

We immediately see a 248 percent increase in operating costs, at $559,204. Coal is now primarily delivered via rail and transfer costs have increased nearly 40 percent, to $100,513.

The worst single attack is on Pool 60, essentially cutting off all river traffic into and out of the Monongahela River. This causes the operator to move the majority of coal by rail to its destination. This disruption causes a decrease in river transport, as a large amount of cargo is shipped from the Monongahela River to destinations outside of the Monongahela River and a large amount of cargo is shipped from origins outside of the Monongahela River to destinations on it.

The top 15 worst-case single attacks are listed in Figure 18. Baseline operations are highlighted in green and the most impactful attacks are listed in descending order. The first four worst attacks are attacks on dams. These attacks make river transport through the associated pool impossible, as the loss of a dam means the loss of pool draft and therefore pool navigability. The next most impactful attack occurs at a lock, which makes transfer between the two associated pools impossible.

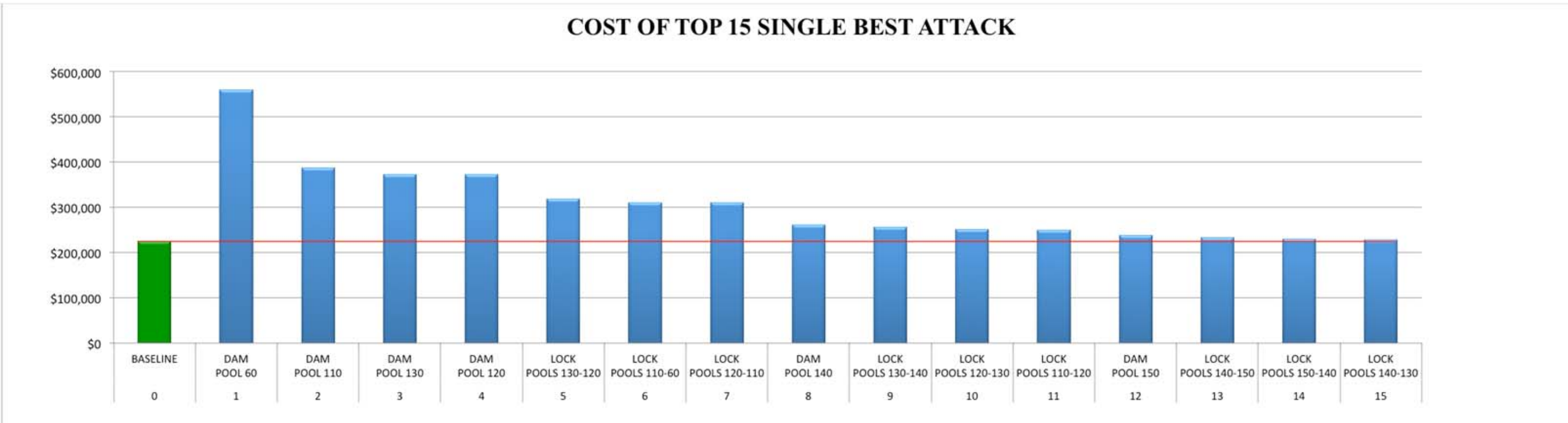


Figure 18. Baseline operating costs (green) and the cost of the best 15 single attacks to the Monongahela River. Dams are attacked first, restricting navigation through pools. Locks are then attacked, restricting the ability to transit between pools.

C. MULTIPLE SIMULTANEOUS ATTACKS

Simultaneous disruptions may occur at multiple, separate locations. These simultaneous attacks will necessarily increase costs above the cost of a single worst-case disruption. The worst-case scenario for two simultaneous attacks occurs at Pool 60 and Pool 130. This attack causes total operating costs to rise to $598,421. The majority of coal is then shipped via rail, while some is still moved via river. Interestingly, transfer costs decrease from the single attack scenario, as the operator chooses to ship directly from source to destination via rail, rather than transferring coal to the river, partly using the river, then transferring to rail for the remainder of the trip. With two simultaneous attacks, the operator avoids multiple loading and offloading transfers. Table 5 displays these statistics. We maintain this standard of conveying operating results throughout the remainder of this analysis. As attacks increase, barge use decreases, and rail car and truck use increase. Table 5 deconstructs the costs associated with each mode of transport, beginning with zero attacks and ending with five simultaneous attacks. Looking at the MODAL COST, it becomes apparent that transportation costs rise drastically following the initial attack(s).

# ATTACKS	MODE	TONS		TON-MILES	MODAL COST	TOTAL COST
0	river	1,244,879	711 barges	19,176,963	$153,416	$225,449
	rail			0		
	road			0		
	transfer	320,150		320,150	$72,034	
1	river	938,331	536 barges	4,438,750	$35,510	$559,203
	rail	123,074	1230 rail cars	8,463,616	$423,181	
	road			0		
	transfer	446,722		446,722	$100,513	
2	river	213,250	121 barges	894,238	$7,154	$598,421
	rail	153,742	1537 rail cars	10,208,468	$510,423	
	road			0		
	transfer	359,304		359,304	$80,843	
3	river	8,819	5 barges	53,975	$432	$602,146
	rail	166,354	1663 rail cars	10,593,602	$529,680	
	road			0		
	transfer	320,150		320,150	$72,034	
4	river			0		$602,824
	rail	169,867	1698 rail cars	10,603,398	$530,170	
	road	2,964	118 trucks	6,206	$621	
	transfer	320,150		320,150	$72,034	
5	river			0		$602,824
	rail	169,867	1698 rail cars	10,603,398	$530,170	
	road	2,964	118 trucks	6,206	$621	
	transfer	320,150		320,150	$72,034	

Table 5. Most impactful simultaneous attacks: 0 through 5. For 2 simultaneous attacks, 213,250 tons of coal is transported via river and 153,742 tons of coal is transported via rail. The cost to operate the system becomes $598,421.

The worst-case scenario for three simultaneous attacks occurs at Pool 60, Pool 130, and Pool 150. These attacks cause total operating costs to rise to $602,145. The majority of coal is shipped via rail, while some is still moved via river and transfer costs continue to decrease.

The worst-case scenario for four simultaneous attacks occurs at Pool 60, Pool 110, Pool 130, and Pool 150. These attacks cause total operating costs to rise to $602,824. The majority of coal is shipped via rail, while some is still moved via river and transfer costs continue to decrease. Finally, some coal is moved via road.

The worst-case scenario for five simultaneous attacks occurs at Pool 60, Pool 110, Pool 120, Pool 130, and Pool 150. These attacks cause total operating costs to plateau at $602,824.

The Operator's Resiliency Curve in Figure 19 illustrates the increased costs associated with attacks 0 through 5. This increased cost to operate the system represents the attacker's "return on investment." Each attack increases costs; however, after only two attacks, the incremental costs become very small.

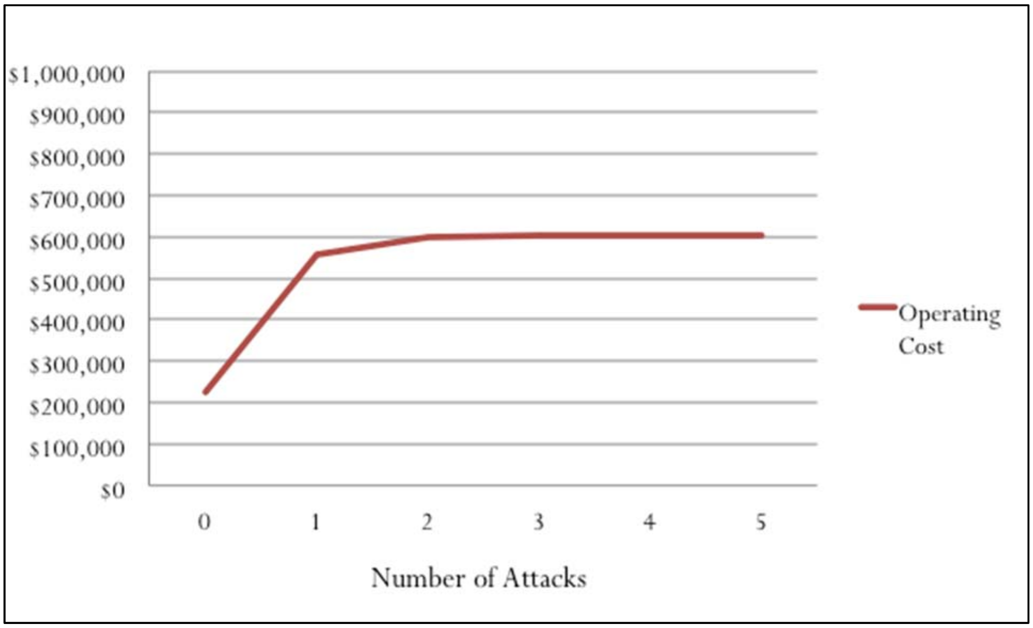


Figure 19. Operator's Resiliency Curve. For an increasing number of attacks on this system, there is a diminishing return to the amount of incremental cost that can be forced upon the operator.

Our analysis shows the results of single attacks and multiple attacks significantly increase operating costs. Additionally, we note attacks most often occur on dams, to eliminate the use of pools, or on locks, to restrict movement between pools. These attacks focus on frustrating the flow of coal into and out of our narrowed AOI on the Monongahela River. We also notice attacks toward the middle of the Monongahela River, disrupting the large amounts of internal coal flows.

Table 6 breaks out the best attack locations, total cost, and cost increases from baseline operations for attacks ranging from zero to five simultaneous attacks. The financial impact of a 2-attack scenario rises to 265 percent increase from baseline operations. However, all subsequent combinations of attacks (3-attacks, 4-attacks, and 5-attacks) result in less than 2 percent increase in costs.

1 week					
# ATTACKS	RANK	BEST LOCATION OF ATTACK	COST	COST INCREASE FROM BASELINE	% COST INCREASE FROM BASELINE
0	0	BASELINE	$225,449		
1	1	DAM POOL_60_IN POOL_60_OUT	$559,203	$333,754	248.04%
	2	DAM POOL_110_IN POOL_110_OUT	$388,037	$162,588	172.12%
	3	DAM POOL_130_IN POOL_130_OUT	$373,038	$147,589	165.46%
	4	DAM POOL_120_IN POOL_120_OUT	$372,403	$146,954	165.18%
	5	LOCK POOL_130_OUT POOL_120_IN	$319,173	$93,724	141.57%
	6	LOCK POOL_110_OUT POOL_60_IN	$310,903	$85,454	137.90%
	7	LOCK POOL_120_OUT POOL_110_IN	$310,451	$85,002	137.70%
	8	DAM POOL_140_IN POOL_140_OUT	$261,268	$35,819	115.89%
	9	LOCK POOL_130_OUT POOL_140_IN	$255,921	$30,472	113.52%
	10	LOCK POOL_120_OUT POOL_130_IN	$250,601	$25,152	111.16%
	11	LOCK POOL_110_OUT POOL_120_IN	$249,123	$23,674	110.50%
	12	DAM POOL_150_IN POOL_150_OUT	$237,558	$12,109	105.37%
	13	LOCK POOL_140_OUT POOL_150_IN	$233,065	$7,616	103.38%
	14	LOCK POOL_150_OUT POOL_140_IN	$229,659	$4,210	101.87%
	15	LOCK POOL_140_OUT POOL_130_IN	$228,686	$3,237	101.44%
2	1	DAM POOL_60_IN POOL_60_OUT DAM POOL_130_IN POOL_130_OUT	$598,421	$372,972	265.44%
	2	DAM POOL_60_IN POOL_60_OUT DAM POOL_120_IN POOL_12_OUT	$584,922	$359,473	259.45%
	3	DAM POOL_60_IN POOL_60_OUT LOCK POOL_130_OUT POOL_120_IN	$583,628	$358,179	258.87%
	4	DAM POOL_60_IN POOL_60_OUT DAM POOL_110_IN POOL_110_OUT	$580,226	$354,777	257.36%
	5	DAM POOL_60_IN POOL_60_OUT LOCK POOL_120_OUT POOL_110_IN	$578,731	$353,282	256.70%
3	1	DAM POOL_60_IN POOL_60_OUT DAM POOL_130_IN POOL_130_OUT DAM POOL_150_IN POOL_150_OUT	$602,145	$376,696	267.09%
4	1	DAM POOL_60_IN POOL_60_OUT DAM POOL_110_IN POOL_110_OUT DAM POOL_130_IN POOL_130_OUT DAM POOL_150_IN POOL_150_OUT	$602,824	$377,375	267.39%
5	1	DAM POOL_60_IN POOL_60_OUT DAM POOL_110_IN POOL_110_OUT LOCK POOL_120_OUT POOL_110_IN DAM POOL_130_IN POOL_130_OUT DAM POOL_150_IN POOL_150_OUT	$602,824	$377,375	267.39%

Table 6. Impact of multiple simultaneous attacks. With 5 simultaneous attacks, Pools 60, 110, 130, and 150 are attacked, as well as the lock from Pool 120 to 110. This results in an operating cost of $602,824, which is an increase from the baseline of 267.39%.

Interestingly, the system seems to be fairly resilient following just two attacks. This results from a robust rail network and modeling assumptions that make the rail network nearly invulnerable. It takes five attacks to force coal onto the most expensive form of transportation: trucks on roads. Again, the transfer costs have receded to pre-attack costs, as the model no longer finds it advantageous or possible to conduct more than one loading and one offloading action per shipment.

D. ALTERNATIVE SCENARIOS

To this point our study has considered single and multiple attacks on our network. Now, we will consider alternative scenarios involving (1) perfect protection of the dams along the river and (2) perfect protection of both locks and dams along the river. This perfect protection equates to the invulnerability of those assets (i.e., dams and locks).

The Operator's Resiliency Curve (denoted by green triangles) in Figure 20 illustrates the decreased impact of attacks on our system when pools are perfectly protected. Each set of attacks results in a reduced return on investment for the attacker. This seems reasonable because the most damaging attacks under normal operating conditions are on pools.

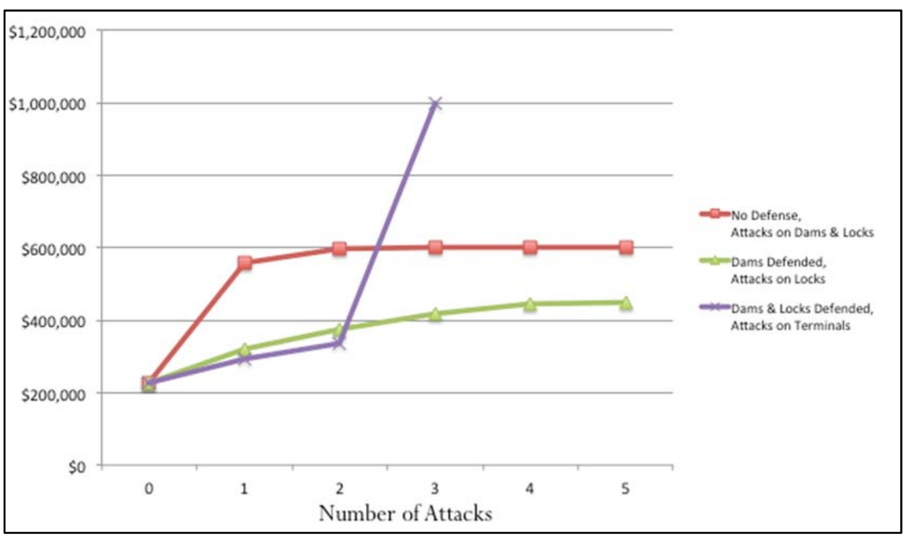


Figure 20. Operator's Resiliency Curve with alternative scenarios of (1) no defense, where attacks occur on dams and locks (denoted by red squares), (2) dams defended, where attacks occur on locks (denoted by green triangles), and (3) dams and locks are defended, where attacks occur on terminals (denoted by purple Xs).

Next, we consider the scenario of invulnerable locks and dams. Here we consider perfectly protected locks and dams, where the river is fully navigable. The best single attack occurs on the river transfer arc of a major coal supplier. This attack causes coal to be shipped via rail, rather than river. When the attacker makes two simultaneous attacks, the attacks occur on the river transfer arc and the rail transfer arc of the same major coal supplier. This causes all coal supplied by this mine to be routed on the most expensive mode of transportation: road. Finally, with three simultaneous attacks, this major coal supplier is completely cut off from the network and is unable to move coal onto the network without sending flow along an attacked arc. This incurs an arbitrarily high cost, depending on the penalty we set. In practical terms, this action equates to a cost to reconstitute the damaged arc to enable the movement of coal. The Operator's Resiliency Curve in Figure 20 (denoted by purple Xs) illustrates this behavior. Initially, the return on investment for the first two attack sets is low for the attacker. But, the third attack is significantly harmful.

E. DISCUSSION

The USCG mission emphasizes the defense of waterway infrastructure, so we initially focus on the attack and defense of maritime CI/KR. Not surprisingly, attacks that target dams result in worst-case increase to operating cost, even after river operations adjust flows to minimize transport costs. If the USCG could perfectly protect dams, we observe that, in order to create a worst-case increase in transport cost, an intelligent attacker would instead target locks, but the return on investment for mounting attacks is reduced. Perfect defense of dams and locks shifts the attention of an attacker to coal terminals. In this case, attacking the ability to transfer coal on or off the river at an individual terminal results in less overall cost increase, unless an attacker can isolate a terminal by interdicting completely its ability to send or receive coal. In this case, the resulting "cost" of that isolation can be arbitrarily high, depending on the economic consequences to that terminal. This study considers only a simple cost of isolation that is the same for all terminals; thus the terminals targeted are the ones that move the largest volumes of coal.

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VII. CONCLUSION

The Port of Pittsburgh is a valuable target. With approximately $9 billion in annual commerce, the second largest inland port in the U.S. could be significantly impacted with just a single attack, causing operating costs to rise nearly 150 percent. Adversaries are plotting to disrupt commerce, as evidenced by the recent planned attack on a bridge in neighboring Ohio (Barrett 2012). The use of system interdiction techniques allows us to identify the most critical infrastructure in our system; in our case dams, which support pool navigability. This modeling method allows us to quantify impacts to operating costs and consider various alternative scenarios concerning defense tactics and schemes.

The analysis in this thesis represents an important step forward in assessing the resilience of the Port of Pittsburgh, and the Inland Marine Transportation System more broadly, but there is much more to do.

First, the focus in this thesis on the Monongahela River should be extended to include the entire Three Rivers. We expect broader analysis to confirm the significance of the Monongahela River as a critical segment of the Port of Pittsburgh. We also expect an expanded study to expose valuable targets along the Ohio River, as this river connects our AOI to the larger Marine Transportation System river network. Insights may include a clearer understanding of intermodal transportation behavior as travel distances increase.

Second, it will be important to conduct analysis for horizons longer than a single week. In practice, planning for coal movements occurs over weeks and months, and the repair times for different system components (e.g., dams, locks, transfer terminals, and bridges) could yield different implications for what is most critical. For example, if dams have the longest repair times, then their loss naturally has a bigger impact on the long-term system operation.

Third, just as different system components can have significantly different repair times, it is reasonable to expect that attacks on these components might require a different level of effort. Following the example in Salmerón et al. (2011), it might be reasonable that the attacker's "budget" might be measured in terms of personnel rather than attacks, with each component requiring a different number of individuals for attack success.

Fourth, because the Attacker-Defender model has provisions to allow the operator to move coal in anticipation of an announced disruption to occur in the future, it is possible to use this model to assess the impact of scheduled maintenance. Exploring this model capability in the context of real operations could prove insightful.

Finally, the analysis in this thesis has taken a limited view of "defensive investment," but the model and technique can be extended to consider a comprehensive Defender-Attacker-Defender formulation in which one considers a list of possible investment options, ranging from hardening to redundancy to capacity expansion, each with its own cost. Then given a fixed limited investment, the DAD model will identify the combination(s) of investment that yield the most resilient system. Moreover, it then becomes possible to consider how different levels of investment lead to improved resilience. Identifying such defensive "return on investment" tradeoffs will be an important avenue for future work, particularly in an environment of diminished fiscal budgets.

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