A Functional All-Hazard Approach to Critical Infrastructure Dependency Analysis

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Abstract

The critical infrastructures protection landscape is a vast and varied pattern of independent, but interconnected infrastructure systems that are essential to the function of our modern society. The U.S. policy on critical infrastructure protection has been continually evolving since the "President's Commission on Critical Infrastructure Protection" was published in 1997. In response to these policies, federal, state, and local governments, along with research institutions, have invested a substantial amount of time and effort into identifying and analyzing critical infrastructure, their functions, and dependencies/interdependencies to better understand their vulnerabilities. To date, the ability to assess vulnerabilities, resiliency, and priorities for protecting interdependent critical infrastructure systems from an all-hazards perspective remains a difficult problem. In this paper we introduce the All-Hazards Analysis (AHA) methodology, which provides an integrated functional basis across infrastructure systems, through the implementation of a common language and a scalable level of decomposition to effectively evaluate the resilience of interconnected infrastructure systems. AHA models infrastructure systems as directed multidimensional graphs, which enable the evaluation of cross-sector interdependencies prior to, during, and after disruptive events. Finally, and by design, AHA enables the cross linking of data taxonomies to enable more effective data sharing, such as the National Critical Functions (NCF) and Infrastructure Data Taxonomy (IDT).

Keywords: Dependency, Interdependency, Critical Infrastructure, Cascading effects, Functional Decomposition, Modeling and Simulation

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Introduction

Infrastructure systems are the backbone of modern societies and are critical for well-functioning communities. By design these systems are engineered to optimize the production, transport, transmission, and consumption of goods and services. However, natural and man-made hazards have the potential to disrupt these services, thus impacting normal community functions. Reports such as the "American Society of Civil Engineers' Report Card for America's Infrastructure" (American Society of Civil Engineers 2021) and the "President's Commission on Critical Infrastructure Protection (PCCIP)" (1997) have raised awareness about the need to maintain, protect, and enhance the resilience of our infrastructure systems and, in turn, the resilience of our communities.

Policymaking and decision support for the resilience of communities must include awareness and appreciation of the interconnectedness of facilities and systems across the infrastructure sectors (National Academies of Sciences 2019). The satisfactory functioning of one system may depend on, or be required for, the satisfactory functioning of another system, in either the same or a different sector. The PCCIP report emphasized that these complex and interdependent systems have become increasingly vulnerable to cascading, escalating, and common cause failures. Since the report was published in 1997, a substantial body of research has been devoted to identifying, understanding, and analyzing critical infrastructure and improving the general understanding of infrastructure interdependencies (Haggag et al. 2020; Bloomfield et al. 2017; Ouyang 2014; Rinaldi, Peerenboom, and Kelly 2001; Satumtira and Dueñas-Osorio 2010; Wang et al. 2019).

The increase in situational awareness brought about by this research has enabled resource planners and emergency response organizations to effectively mitigate potential vulnerabilities and direct response and recovery efforts following a natural or man-made event. However, in February 2021, the Texas Polar Vortex caused a complex series of cascading disruptions to power, natural gas, and water infrastructure, which left 4.5 million homes and business without power and a significant number without water for multiple days. This vortex crippled the supply chains and transportation networks. It was also directly or indirectly responsible for over 100 deaths (King, Rhodes, and Zarnikau 2021). Events like this demonstrate that the ability to routinely identify cross-sector vulnerabilities and prioritize mitigation measures from an all-hazards perspective is critical but remains a difficult problem (Osei-Kyei et al. 2021).

This paper presents the All-Hazards Analysis (AHA) methodology, which is a functionbased analytical framework designed to enable the evaluation of critical infrastructure systems and their dependency relationships. AHA provides the ability to store and model infrastructure systems as linked spatial multi-graphs, which provide an intuitive and natural representation (Boccaletti et al. 2014). The framework is an implementation of a functional basis approach designed to decompose engineered systems into their functional components. Functional reasoning is a widely used technique in the field of engineering to design products and systems to ensure their structure enables their intended purpose (McInnes, Eames, and Grover 2021; Nielsen et al. 2015; Stone and Wood 1999; van Eck, McAdams, and Vermaas 2007). Leveraging this approach overcomes many of the challenges encountered when assessing infrastructures systems, including the common thought expressed by many system operators that if you assess one water treatment plant, you have only assessed one water treatment plant— utilizing functional reasoning minimizes the need for in-depth engineering detail. The primary contribution of the AHA framework is that it provides an integrated functional basis across infrastructure systems, which provides both a common language and a scalable level of decomposition to effectively evaluate the resilience of existing infrastructure systems. These characteristics provide a robust and repeatable foundation for evaluating interconnected infrastructure system vulnerabilities to both man-made and natural hazards and the potential consequences of their disruption. Section 2 provides a background on critical infrastructure and dependency concepts, including alternate assessment and modeling methodologies. Section 3 describes the AHA methodology and its outputs. In Section 4, an application of the AHA methodology is provided by creating a functional basis for refined petroleum product pipelines and utilizing the basis to construct an executable model of the Colonial Pipeline Refined Product System. The model was used to simulate the consequence of the recent ransomware attack that affected the pipeline's operational state. The concluding remarks and proposed future research needs are discussed in Section 5.

Background

General Concepts

Table 1 provides brief descriptions of terms relevant to this research.

Table 1. Infrastructure analysis terms and definitions.

Infrastructure Analysis Terms and Definitions		
Term	Definition	Source
Infrastructure	An engineered system and/or facility that enables and enhances a community's ability to meet societal demands by facilitating the production, transport (transmission), and consumption of goods and services. They can be composed of multiple interconnected facilities, assets, and software that perform specific actions to enable the functions of the system.	Expanded from INCOSE Engineered System Definition (INCOSE Website)

Dependency	The one-directional reliance of an asset, system, network, or collection thereof—within or across sectors—on an input, interaction, or other requirement from other sources in order to function properly.	Department of Homeland Security, 2013
Critical infrastructure	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, national economic security, national public health or safety, or any combination of those matters.	President's Commission on Critical Infrastructure Protection, 1997
Resilience	The ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance, and the capacity of an organization to recognize hazards and threats and make adjustments that will improve future protection efforts and risk reduction measures.	Department of Homeland Security, 2018
All-Hazards	A threat or an incident, natural or man-made, that warrants action to protect life, property, the environment, and public health or safety, and to minimize disruptions of government, social, or economic activities. It includes natural disasters, cyber incidents, industrial accidents, pandemics, acts of terrorism, sabotage, and destructive criminal activity targeting critical infrastructure.	President's Commission on Critical Infrastructure Protection, 1997
System function	The primary input and output relationship of an infrastructure system, having the purpose of performing an overall task, typically stated in verb-object form.	Adapted from Stone and Wood (1999)
Function	A description of an operation to be performed by a device or asset, expressed as the active verb of the function.	Adapted from Stone and Wood (1999)
Dependency Type (flow)	A commodity, service, or datum that is exchanged between facilities or sub-facilities with respect to time. Expressed as the object of the function, a flow is the recipient of the function's operation.	Adapted from Stone and Wood (1999)

Dependency Profile	A description of a facility or sub-facility in terms of dependencies that are required to achieve the overall function or purpose.	Idaho National Laboratory (2021)
Functional Basis	A design language consisting of a set of functions and a set of dependencies that are used to enable a system function.	Adapted from Stone and Wood (1999)
Multi-graph (Multi-dimensional Network)	Formally defined as edge-labeled multi-graph $\boldsymbol{G = (V, E, D)}$ where $\boldsymbol{V}$ is a set of nodes, $\boldsymbol{E}$ is a set of labeled edges, and $\boldsymbol{D}$ is a set of labels representing the dimensions.	Boccalett *et. al.* (2014) & Kivela *et. al.* (2014)

Infrastructure Dependency Modeling and Simulation

The analysis of dependencies among infrastructure assets and systems has interested researchers from a variety of fields, including not only engineering and mathematics but also social science. Interdisciplinary efforts to improve resilience have incorporated modeling of infrastructure networks and simulations of disruptions to prepare or respond to incidents and improve the quality of life of communities. Literature reviews of resilience research contributions by those studying interdependency of infrastructure, such as Satumtira and Dueñas-Osorio (2010), Ouyang (2014), and others focus on the variety of modeling and simulation approaches to describe and quantify dependencies, risk, cascading impacts, and their impact on overall resilience across time and space.

Satumtira and Dueñas-Osorio examined the recurring themes and dimensions by which infrastructure dependency modeling and simulation research was available in published literature (Hernandez-Fajardo and Dueñas-Osorio 2013). In their review, they found the researchers' chose a mathematical modeling method that had the strongest approach and include input-output, agent-based, and network and graph-theory techniques. Other cited dimensions of study include the objective of the modeling effort (e.g., risk and vulnerability analysis, mitigation measures, prediction, and failure propagation awareness), scale of analysis (system-of-systems to specific networks and assets), and the targeted discipline (engineering to study optimization of resources for reliability, economics to study financial risk, and social sciences to study decision making and governance).

The review of infrastructure interdependency research by Ouyang (2014) centered on the emerging concept of infrastructure system resilience. While the focus was on the modeling approaches to evaluate resilience, the author provided a useful classification of types of interdependencies—not all are physical (based on materials input and output between systems), but can be cyber (information), geographic (based on proximity), logical (policy, regulatory, or market-based), and even more conceptual (quantified by criticality or exclusivity); these distinctions are elaborations of typologies of Rinaldi, Peerenboom, and Kelly (2001) and Dundenhoeffer, Permann, and Vermass (2007). Models, in their context, include empirical approaches, based on historical accident or disaster data and expert experience, that reconstruct interdependencies from reports and records of past events such as hurricanes (Chang et al. 2007) or terror attacks (Mendonça and Wallace 2006). Like Satumtira and Dueñas-Osorio (2010), the review delineates agent-based and economic approaches, and details the growing body of dependency research that leverages network-based approaches, further differentiating between those based on topology of networks (Buldyrev et al. 2010; Hernandez-Fajardo and Dueñas-Osorio 2013), and flow-based methods that represent capacities and storage at nodes and along links (Ouyang et al. 2009).

In both reviews, discussions of limitations to infrastructure interdependency studies began with the challenge of data access and collection. Empirical approaches to infer interdependencies are limited in scope because they are based on the type of hazard or incident and the incident context (Brown, Beyeler, and Barton 2004) and lack a uniform data collection method (including definitions of key concepts like resilience or types of interdependencies). Relevant data for useful modeling can be difficult to access due to confidentiality, business sensitivity, or liability concerns (Rinaldi, Peerenboom, and Kelly 2001), and research innovations include the discovery of novel techniques for handling such sensitivities.

Data acquisition and the availability of accurate validation techniques using limited data is one of the several interdependency research gaps noted recently by Haggag and Ezzeldin in a review of the interdependence of infrastructure to analyze the resilience of cities (Haggag et al. 2020). Their text-processing meta-analysis of over 120 publications in the area led to an inductive classification into nine topic areas, including definitions and descriptions of resilience, risk, and critical infrastructure in general, a survey of infrastructure interdependency modeling techniques (similar to the focus of other reviews), and a focused topic area of application of complex network theory, which continues to generate particular interest in the field. Further distinction in this analysis was between physical and functional networks, mirroring the topology vs. flow distinctions in (Ouyang et al. 2009). Along with the challenge of data access and completeness, other gaps in research are presented by the authors including the incomplete quantification of dependency types, the inability of research to scale entire systems of systems, the lack of linkages between hazards to the performance of systems, and the challenge of incorporating time and the dynamic behavior of systems to respond to shocks and changes.

The research presented in the following sections joins the body of literature that is addressing these challenges, leveraging graph representation techniques to model nodes and links in systems (and between systems), and proposing novel techniques to create defensible and verifiable infrastructure dependency data with a multi-source approach. The framework differentiates types and quantities of dependencies, models generic types of infrastructure to enable rapid development of dependency information for high-level analysis, and builds capabilities to enhance situational awareness and assess resilience.

Methods

The AHA methodology is an analytic framework developed to enable the evaluation of critical infrastructure dependencies for the purpose of identifying potential vulnerabilities and consequences of system disruption. The objective of the AHA framework is to provide a scalable, robust, and repeatable process for the development and analysis of functional dependency models of interconnected infrastructure systems, and to document their spatial and temporal characteristics under all-hazard conditions.

Function-Based Asset Taxonomy

The initial stage of the AHA methodology is the development of a function-based asset taxonomy that enumerates a standard set of functions and flows by asset types. This process is based on the concept of functional decomposition and leverages a modified version of the functional basis approach first proposed by Stone and Wood (1999). This results in a hierarchal list of function-based asset models, which are referred to as dependency profiles. Breaking down infrastructure systems in this manner provides a scalable systematic and precise mechanism to collect and communicate domain specific system engineering knowledge (Nielsen et al. 2015; Stone and Wood 1999; van Eck, McAdams, and Vermass 2007).

Structurally, the AHA function-based asset taxonomy is developed around the primary purpose or task (function) of a system and includes two primary structures, facility and subfacility types (asset), and dependency types (function or flows). The system taxonomy is created through an iterative process that incorporates the following steps: (1) facility-type enumeration, (2) dependency type enumeration, and (3) dependency profile generation, which are described in greater detail below.

The facility type enumeration step provides the ability to enumerate the type of facilities associated with a particular infrastructure system and is broken into two categories, facilities and subfacilities. This step results in an ordered list of facility types that are used to enable the function of an infrastructure system. The hierarchical approach allows for inheritance of properties and aggregation of functions eliminating the need to create entries for all potential functional combinations. A facility type represents a major infrastructure type (e.g., data center) and a subfacility represents internal assets and devices that are used to facilitate operations of internal or external systems and facilities (e.g., uninterruptable power supply). Each type can be assigned specific properties that enable additional capabilities, such as advanced modeling and simulation. These properties describe important characteristics about the facility type, such as storage capacity or generation capability.

The dependency types enumeration step provides the ability to enumerate the commodities, services, and data types that are required by, transported by, or produced by an infrastructure system, facility, or asset. Dependency types are broken down into three distinct categories: general, network, and transportable. A general dependency type represents a commodity or service that can be directly mapped between two facility types. A network dependency type represents a service network that can transport a transportable dependency type. For example, freight rail transport dependency type is a network and thus can be utilized to transport other commodities, such as agricultural products. Each dependency type can be assigned specific properties to enable additional capabilities such as advanced modeling and simulation.

The dependency profile step facilitates the creation of general facility profiles that describe the range of inputs and outputs required by a particular system, facility, or asset type and the relationship is described in a verb-object form (e.g., requires electricity or provides electricity) as shown in Figure 1. Dependency profiles represent black boxes of operational flows of commodities and services and as implemented, dependency relationships are passed up the taxonomic tree to facilitate comprehensive sector and system level profile development. Further, each relationship is assigned a general measure of criticality based on the following categories derived from Department of Defense Protection Failure Criticality Levels (Department of Defense 2013).

Critical or Facility Down (4): Production down or major malfunction resulting in an inoperative condition. Operators unable to reasonably perform their normal functions. Consumers without service. The specific functionality is mission critical to the system and the situation is considered an emergency.

Significant Impact (3): Critical loss of functionality or performance resulting in abnormal operation. Operators unable to perform their normal functions. Major feature or product failure; inconvenient workaround or no workaround exists. The facility is usable but severely limited. Consumers with limited or impaired service.

Normal or Minor Impact (2): Moderate loss of functionality or performance resulting in abnormal operations. Operators impacted in their normal functions. Minor feature or product failure, convenient workaround exists with minor performance degradation and not impacting production.

Low or No Impact (1): Minor loss of functionality, product feature requests, how-to questions. The issue consists of how-to questions including issues related to one or multiple modules and integration, installation and configuration inquiries, enhancement requests, or documentation questions.

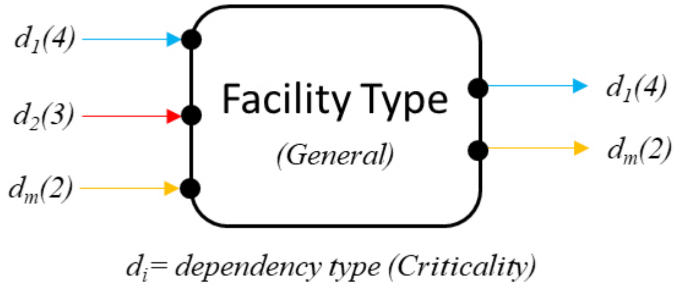

Figure 1. Example Dependency Profile.

It is important to note these are guides and can be altered when developing actual dependency relationships between facilities. Finally, output relationships are assigned a functional type, which include source, storage, and transport (default). Source type indicates that a facility or device type can produce a commodity, service, or datum. Storage type indicates that a facility or device type can store a commodity, service, or datum. Transport type indicates that a facility or device type simply passes or diverts a commodity, service, or datum.

When applied correctly, this stage results in a comprehensive, scalable, and non-redundant functional basis of an infrastructure system and when combined with coherent definitions, provides a universal assessment language and conceptual model.

Function-Based Infrastructure Dependency Models

The second stage of the AHA Methodology is the development of system and facilities specific dependency models. These are modeled as a directed multidimensional network (Boccaletti et al. 2014) leveraging a modified version of the approach described by Svendsen and Wolthusen (2007). This stage consists of a three-step process that requires the loading of system facilities and sub-facilities, which represent the vertices of the graph, the assignment of dependency links between facilities of a system, and the assignment of intersystem dependency links. This includes the initialization of storage and link parameters. A comprehensive mapping will trace the commodity, service, or datum type from the time it enters until it exits the system or facility.

The first step in developing a system specific dependency model is the loading of system facilities and sub-facilities. During the loading process, individual facilities will receive their taxonomic assignment and they will inherit the respective dependency profile. In addition to facility type the following elements of information can also be included during the loading process: Name (Required), Owner, Operator, Address, ZIP Code, State, County, Country, Confidence, Latitude (Required), and Longitude (Required). Confidence category assignments are assigned to each of the facilities based on the underlying source information and include the follow values:

- **Vetted (4)** – Information has been recently confirmed by infrastructure owner or operator.
- **High (3)** – Information has been confirmed by infrastructure owner or operator in the past or derived from recently published and openly available owner or operator or derived from recent provided regulatory data.
- **Moderate (2)** – Information has been published in the past by owner or operator or in regulatory data or derived from recently published third-party sources. Some heuristics.
- **Low (1)** – Outdated information or heuristics.

The second step in this stage is the assignment of dependency relationships between facilities based on their respective profile. Profiles enforce how a facility functions and defines their dependency interfaces resulting in a consistent and defensible model. Creating a dependency relationship between facilities will require that one of the facilities can provide a commodity or service and the other requires the same commodity for operations. As implemented, the AHA application automatically enforces these rules and presents potential facilities relationship in an ordered list by distance. Dependency relationship parameters include:

- **Strength** – As defined above and can be inherited from the profile or overridden based on facility specific information.
- **Confidence** – As defined above.
- **Precent Commodity** – Defines the degree to which a specific dependency relationship can provide the entire required amount for normal operation.
- **Contingency Type** – Categorizes a dependency relationship as either primary or contingent. Dependency relationships are considered primary by default. Contingent relationship are alternate sources that are used in the event a primary dependency source is disrupted. A contingent relationship requires time to switch for a variable to be set.
- **Storage Duration** – Number of minutes a dependency relationship can be maintained after initial disruption if defined as a storage-type dependency.

The third and final step of regional dependency model creation is the aggregation of the distinct system dependency model into a single cohesive representation. The aggregated model provides a functional dependency model of interconnected infrastructure systems, and with documented spatial and temporal characteristics directly related to system operations. The resulting model enables direct simulation of system behavior based on steady state design parameters.

Results: Colonial Pipeline Case Study

On May 7, 2021, the Colonial Pipeline Company reported that they curtailed operations of their 2.5 million-barrel-per-day refined product pipeline due to a cyber-attack (Colonial Pipeline 2021). The Colonial Pipeline is the primary source of transportation fuels for the east coast with a capacity 3.5 times greater than its only competitor—the Kinder Morgan Product (SE) Pipeline. The carrying capacity of the rail and truck systems severely limit their usefulness and would require almost 3,600 rail cars and 12,500 tanker trucks to match Colonial's volume. The pipeline company's media release left fuel service providers and companies scrambling to secure alternate sources of fuel, and emergency response and government organizations trying to understand and mitigate the potential impacts of the disruption. Although the event did not result in sustained widespread fuel shortages across the east coast, mostly due to the existing terminal storage supplies, some areas did experience significance price inflation and shortages.

This event provides an ideal use case to demonstrate the utility of the AHA framework as a scalable approach to understanding the operation of interdependent critical infrastructure systems and the potential consequence of their disruptions. The use case walks through the functional decomposition of a refined fuel system and the creation of a functional dependency model for the Colonial Pipeline, including its primary first order dependencies.

Refined Fuel Systems Functional Asset Taxonomy Creation

The Colonial Pipeline is the largest and possibly most complex refined product pipeline system in the United States and its continuous operation requires a diverse set of input and output commodities and services to perform its primary function of providing refined petroleum products. According to the Energy Information Agency, the primary uses of refined fuels are for transportation, heating, and power generation. Thus, the primary function of a refined petroleum product pipeline system can be expressed as: *Provide fuels for transportation, heating, and power generation.*

As described above, the next step in the process is the decomposition of a typical refined product pipeline system into its major component facility types, which resulted in the identification of four primary types: a refined product pipeline, a refined a product pump station, a refined product valve station, and a refined product terminal (Pharris and Kolpa 2008). It is important to note that it might be possible to decompose each of these facility types further, for example a refined product valve station could be decomposed into a metering station, a block valve, and Pipeline Inspection Gauge terminal stations. However, this additional layer of decomposition is not required for this use case. This step also included the identification and definition of specific properties for each facility type that would be necessary to model the high-level behavior of the system, such as storage capacity for refined product terminals.

With major component facilities types identified, the dependency link decomposition step looked to enumerate the functional requirements for each type. Table 2 provides the list of the commodities and services, including their general purposes, which were identified for this use case. Table 3 provides a description of the primary function of each facility type, including additional facility types that were required to demonstrate the cross-sector capability.

Table 2. Functional basis: dependency type enumeration.

Dependency Types		Function
Refined Fuels		Used for transportation, heating, and power generation
	Aviation Gasoline	Used for engine fuel in light aircraft
	Diesel	Used for heavy-duty trucks, trains, and heavy equipment
	Fuel Oils	Used for space heating and electric power generation
	Gasoline	Used for transportation fuel for passenger cars and light trucks
	Jet Fuel	Used for fuel in jet aircraft
Electricity		Used for power for equipment and devices
Network Connectivity		Provide communication services for enterprise systems, operational technologies, and other communication enable devices

With a representative example of facility types required to produce, transport, and store refined fuels identified, basic dependency profiles were generated for each type. Figure 2 below presents the profile for a refined product pump station. In this example, refined fuels and electricity dependencies are considered critical dependencies for a pump station and the disruption of their flow would result in an inoperative condition. Network connectivity is considered significant due to the availability of potential workarounds for its intended functions.

The final step in creating the functional basis for a refined product pipeline system is the creation of a conceptual model. Figure 3 below provides a simplified model developed for the Colonial Pipeline use case; however, by design this model could be used for another refined fuel delivery system. The model seeks to describe the major functions, facilities, and assets (sources, storage, and capacity), flow (primary and contingent, capacity), and high-level behaviors of a general system.

Table 3. Functional basis: facility-type enumeration.

Facility Types		Function	Verb-Object Form
Refined Product Pipeline System		Collection of physical facilities designed to transport refined fuels between locations	**Provide** Refined Fuels
	Refined Product Pipeline	Pipeline designed to transport refined fuels	**Provide** Refined Fuels
	Refined Product Pump Station	Facility designed to pump refined fuels through a pipeline	**Provide** Refined Fuels
	Refined Product Storage Terminal	Facility designed to store refined fuels	**Provide** Refined Fuels **Store** Refined Fuels
	Refined Product Valve Station	Facility designed to control, and measure refined fuel flows within a pipeline system	**Provide** Refined Fuels
Petroleum Refinery		Facility designed to produce refined fuels	**Produce** Refined Fuels **Requires** Electricity
Substation		Facility designed to distribute electric energy	**Provide** Electricity
Airport		Facility designed to facility air transportation services	**Requires** Refined Fuels

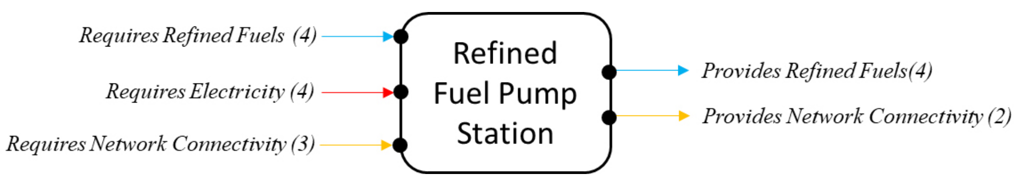

Figure 2. Dependency Profile for a Refined Product Pump Station.

The resulting model serves two primary purposes, one is to act as a guide for developing system specific models and the other is to provide a general mechanism to answers high-level questions regarding the operation of a refined product pipeline system and the potential consequences of a disruption. For example, the question "what functions do refined fuel systems enable?" can be directly answered from the evaluation of a functional basis of a typical refined system as shown in Table 4. This capability is valuable during crisis actions where system specific information may not be readily available, Further, the information can be combined with high-level system information to provide greater situational awareness.

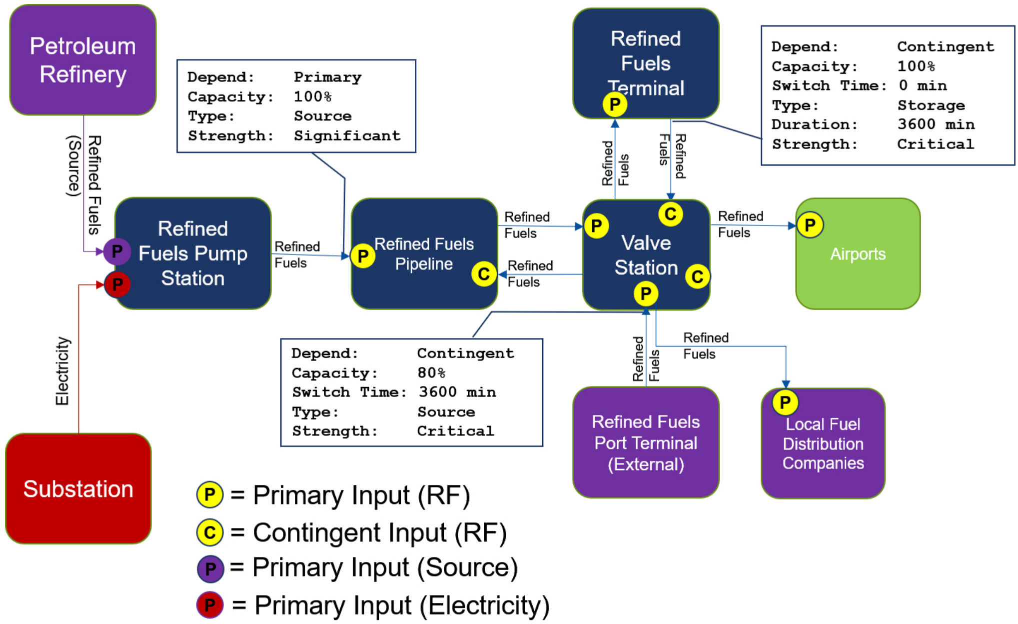

Figure 3. Simplified Conceptual Model Developed for the Colonial Pipeline Use Case.

Table 4. General use of functional basis for high-level question answering.

Question: What functions do refined fuel systems enable?		
Facility Type	Facility Function	Dependency Type Function
Refined Fuel Systems	Provide Refined Fuels	Used for transportation, heating, and power generation
ANSWER		
Refined Fuel Systems provide refined fuels for transportation, heating, and power generation.		

Colonial Pipeline Systems Functional Model Creation

The second phase of the AHA methodology is the development of a system specific model from a general conceptual model, in this case the development of the functional model of the Colonial Pipeline system shown in Figure 4. It is important to note the model's facilities, dependency links, and parameters were identified from multiple sources, including estimates from subject matter experts and have not been validated with the system operator. The demonstration model incorporated known Colonial Pipeline facilities, petroleum refineries (sources), petroleum storage terminals (storage), and substations. Upon completion of the system specific model, a system generated cross-sector time-sequenced functional model (shown in Figure 5) can be utilized to simulate potential impacts from events such as the Colonial Pipeline ransomware attack.

Figure 4. Development of the Functional Model of the Colonial Pipeline System (Idaho National Laboratory, 2021).

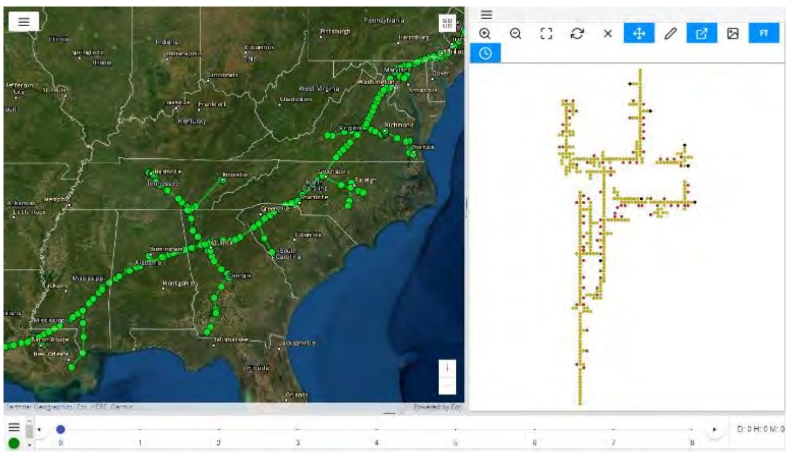

Figure 5. System Generated Cross-Sector Time-Sequenced Functional Model to Simulate Potential Impacts (Idaho National Laboratory, 2021).

To generate similar impacts to what was experienced during the actual ransomware attack, all Colonial Pipeline assets were disabled as the initiating event for the simulation run. As expected, regional storage terminals buffered significant initial impacts of the pipeline curtailment; however, leveraging the criticality measures meant that terminal operators would have transitioned into a state of operations where they would be unable to perform their normal functions and services. This would result in major function or product failure (e.g., spot markets drying up), inconvenient workarounds (e.g., utilizing rail and trunk systems), and limited or impaired consumer services. Without major behavioral changes, the model suggests that the region would begin to experience significant shortages in 3–4 days.

Discussion

Like many other hazard events, the Colonial Pipeline ransomware attack highlighted significant regional dependencies on a single critical infrastructure system, which if disrupted could have far reaching impacts including cascading and escalating failures of interconnected critical infrastructure systems. Understanding critical dependencies and the consequence of disruption is essential for effective policy making, continuity of operation planning, community resilience planning, and emergency management and response (Okatari et al. 2020; Shakou 2019; Cauffman 2018). For example, policy makers need to understand the functions of refined fuel systems and the markets they support with sufficient detail to appropriately incentivize investments in risk mitigation and resilience enhancement by the system owner and the communities they support. Similarly, community resilience planners need sufficient understanding of the systems supporting their region to plan and prepare for potential disruption.

Integrated system functional flow-based analysis techniques provide effective decision support methods and tools that can be used by both decision makers and analysts across industry and government. Functional flow models provide several benefits over other techniques because of their ability to ingest varying levels of data fidelity, which can reduce the burden of information sharing on critical infrastructure owners and operators. In addition, this approach provides the ability to readily evaluate different courses of action related to both policy and infrastructure investment through its ability to seamlessly incorporate cyber-physical infrastructure data and business continuity information. These skills make functional flow modeling ideal for essential and critical function analysis, such as the evaluation of the National Risk Management Center's National Critical Functions or an organization's business continuity capabilities.

However, even with the methods' ability to leverage lower fidelity information it does not fully overcome an organizations willingness to share or validate information due to competitive or legal liability concerns. Thus, additional efforts will need to be made to address the community resilience planners need for enhanced information sharing which is often in opposition to the legal and information security professionals desire to limit or totally restrict sharing.

Conclusion

The AHA methodology and framework provides a consistent, robust, and repeatable process for the development and analysis of computable dependency models of interconnected infrastructure systems. The cross-sector functional basis has the potential to allow multiple analysts to collaborate and share information at the same level of abstraction and enable the generation of reusable functional facility and asset profiles to facilitate a scalable systematic and precise mechanism to collect and communicate domain specific system engineering knowledge. It is the authors' vision that the creation of a formal functional basis will enable the development of comprehensive system-of-systems models that can evaluate the behavior of complex systems and support regional resilience assessments of real-world infrastructure systems.

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Robert Edsall, PhD joined Idaho National Laboratory (INL) in 2015 after spending 15 years as a professor of geography at Arizona State, University of Minnesota, and Idaho State University. He holds a Ph.D. (Geography) and M.S. (Meteorology) from Penn State, after getting a B.A. in Music from Kenyon College in Ohio. He is a specialist in geographic information science (GIS), including GIS, cartography, and data visualization. At INL, he has served as a lead researcher in infrastructure resilience studies, as a leader of teams designing and developing mapping and visualization capabilities, and as a manager of a significant portfolio of direct funded work with the U.S. Department of Homeland Security (DHS) National Risk Management Center.

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