Industry Supply Chain Disruption Analysis for Crater Planning District Commission

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CRATER PLANNING DISTRICT COMMISSION

CCALS Commonwealth Center for Advanced Logistics Systems

UNIVERSITY of VIRGINIA CENTER for RISK MANAGEMENT of ENGINEERING SYSTEMS

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Executive Summary

This report describes effort of the Commonwealth Center for Advanced Logistics Systems and by the University of Virginia Center for Risk Management of Engineering Systems in response to needs outlined by the Crater Economic Development District.

The report extends the resilience register methodology to perform supply chain disruption analysis. Specifically this report addresses the long and short-term disruptions which have occurred due to COVID-19 with an emphasis on business logistics for distribution, warehousing, and transportation sectors. This report addresses the impact of other disruptive scenarios on the Crater region, addressing projects, employers, and logistics assets.

The methodology is implemented in four steps. In step one begins by collecting a set of initiatives – these could be projects, assets, policies, technologies, or other investments. additionally, the resilience register outlines performance criteria which reflect organizational goals. Each initiative is then scored based on how well it addresses performance criteria.

In step two, the register identifies disruptive events and groups these events into scenarios. The register measures the influence of each scenario on each initiative and performance criteria.

In step three, the resilience register outlines how the priority of initiatives change when exposed to disruptive scenarios. The initiatives are ranked by their values under a baseline scenario, but the register displays how rankings change due to disruption.

In step four, these disruptions are aggregated to determine which scenarios are the most disruptive to the system as a whole. This process is iterative – stakeholders update criteria, initiatives, emergent conditions, and scenarios after viewing the results of the initial analysis.

This report presents four case studies. Case one analyzes projects from the 2021-2022 Crater Planning District Commission project priority list using the resilience register. Case two uses the re-

silience register to assess the impacts of disruptions to several of the largest employers in the Crater region. Case three employs the resilience register to analyze industry supply chain disruptions.

Case four utilizes the modality diversion model to identify origin regions, destination regions, and commodities that are at risk of moving through another region of the country for import or export. This combined with scenario analysis enables identification of stable priorities.

Across all analyses, the natural disaster and pandemic scenarios were the most disruptive to the region. The cyber security attack scenario ranked third. Other scenarios such as a funding decrease, increased environmental regulation, climate shift, and the green technology movement are not as disruptive.

This analysis indicates that abrupt, unpredictable scenarios are more disruptive to the Crater region and associated industry supply chains than foreseeable events. Such knowledge indicates that Crater could benefit from investing in initiatives that are resilient to the physical destruction of infrastructure and are not limited by reduced movement of the population.

1 Introduction

1.1 Motivation

The Crater Planning District Commission (CPDC) is a regional planning agency which facilitates local government cooperation to address regional issues and opportunities [4]. The CPDC represents an area of roughly 2,500 square miles with a population of 180,000 across 11 member jurisdictions. These members include the counties of Charles City, Chesterfield, Dinwiddie, Greensville, Prince George, Surry, and Sussex, as well as the cities of Colonial Heights, Emporia, Hopewell, and Petersburg [2]. The CPDC "emphasizes transportation, economic and small business development, the environment, and serves as a convener for major military-related discussion among the region's communities". The primary objectives of the CPDC include [5]:

- Identifying interjurisdictional issues and opportunities
- Establishing plans and policies to address these issues
- Identifying mechanisms through which local governments, the private sector, and non-profits can implement plans and policies
- Promoting cooperation among state and local jurisdictions
- Providing technical assistance and information services to member jurisdictions

The Crater district contains and facilitates several critical infrastructure assets. Interstates 85 and 95 pass through the district – further, I-295 and Route 288 provide links to I-64. The Crater district is linked closely with the Port of Virginia; I-64, Routes 460, 58, and 10, and the M64 Marine Highway (James River) all connect the port and district. Further, the Norfolk Southern and CSX rail lines run through the district, merging in Petersburg. Fort Lee, a United States Army garrison and training installation, represents roughly 10% of the Crater district economy with an annual economic impact of roughly $2.25 billion on the Crater region. Fort Lee financially supports roughly

60,000 people, and hosts the U.S. Army Combined Arms Support Command/Sustainment Center of Excellence, the U.S. Army Quartermaster school, the U.S. Army Ordnance School, the U.S. Army Transpiration School, the Army Logistics University, Defense Contract Management Agency, and the U.S. Defence Commissary Agency [6].

In total roughly 27.6% of the population is employed by government agencies. This includes the Department of Defense, local government agencies such as city and county employees, and correctional facilities including the Greensville Correctional Center and Sussex I and II Correctional Centers. The next largest employment sector is the healthcare and social assistance industry (13.3%), which includes entities such as Central State Hospital, the HCA Virginia Health System, and the Bon Secours Southside Regional Medical Center. Wholesale and retail is the third largest sector (13.2%), which encompasses organizations such as Wal-Mart and Food Lion. The final sector with employment over 10% of the population is manufacturing (10.3%), including employers such as AdvanSix, Gerdau, and DuPont Specialty Products [7].

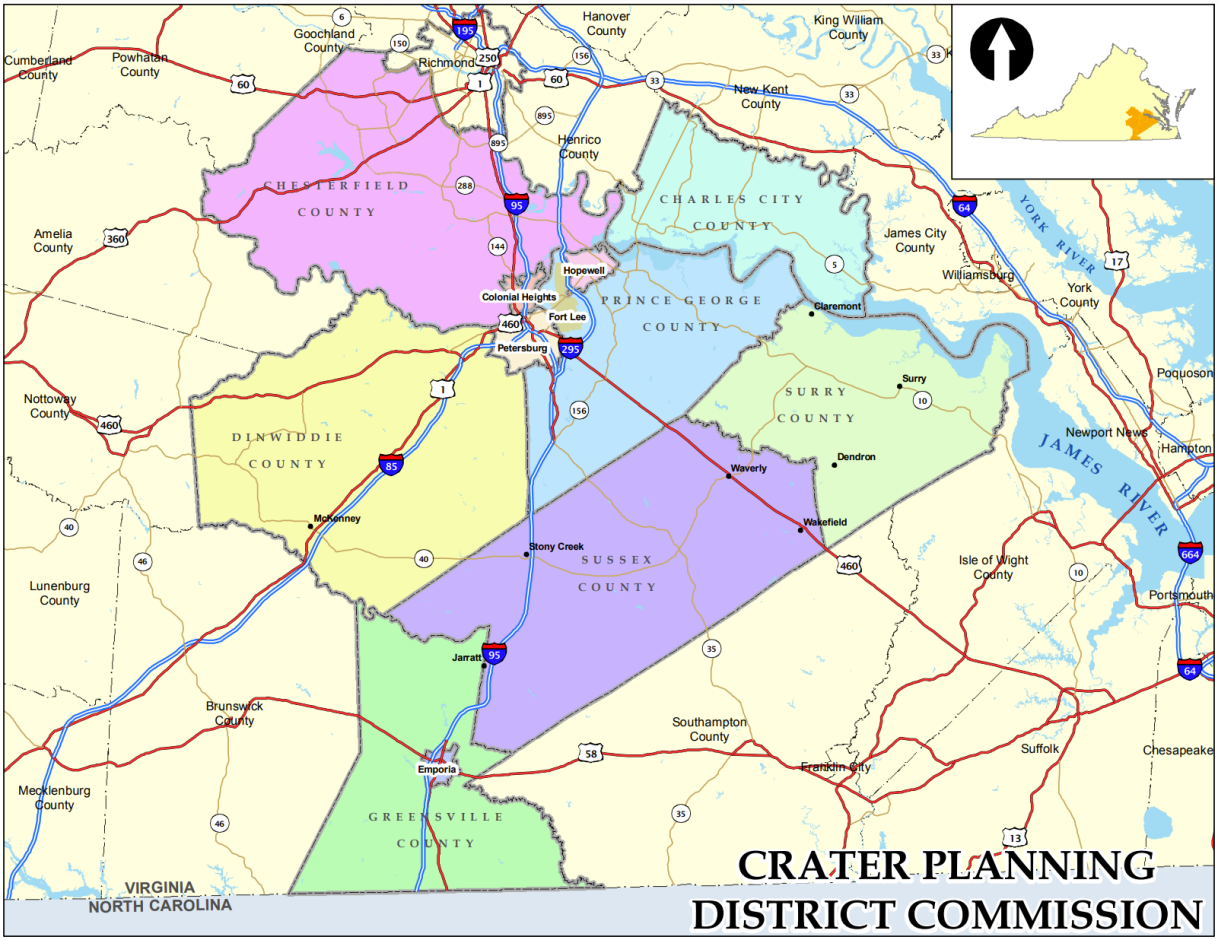


Exhibit 1: Map of the Crater region and its member jurisdictions [1]

The COVID-19 pandemic has had a significant impact on the economy and citizens of the Crater region. Between March and April 2020, the unemployment rate of the region rose from 3% to 11.1%, with 21,175 jobs lost over the period. As of July 2021, the unemployment rate has fallen

to 4.5% [8, 9]. It is estimated that this change in employment represents a loss of $48.1 million of regional GNP in April 2020 alone [2, 9]. The COVID-19 pandemic has spurred the need for the analysis of system disruptions with an emphasis on pandemics. This report focuses on enterprise risk, emphasizing industry supply chain disruptions. The analysis addresses the impact of pandemics as well as other disruptive events such as natural disasters, political changes, and cyber attacks.

1.2 Purpose and Scope

Developing resilient and risk-tolerant systems requires an assessment of priorities and observing how these priorities change under various exogenous scenarios [10–12]. The impacts of COVID-19 have increased the need for methodologies that consider risk to economic priorities [9, 13, 14]. Given the uncertainty in the occurrence of COVID-19 and similar events, it is difficult to prioritize organizational initiatives – initiatives may conflict with one another or serve a highly specialized purpose within the system [15]. The impact of scenarios on organizational preferences complicates prioritization efforts further, especially as preferences evolve over time [16]. As such, it is critical to develop methodologies and techniques to prioritize initiatives in a way that aligns with the objectives of the organization, even as priorities change [17]. This report presents an extension of the resilience register methodology, a regimented technique used to assist decision makers with prioritizing initiatives. The resilience register allows a decision maker to compare several initiatives at once – such as potential projects, technologies, or policies – by observing how rankings change under various disruptive scenarios. The effect of this analysis is twofold: first, it assists an analyst in prioritizing initiatives and second, it highlights which scenarios are the most disruptive to the target system [18]. Such assessments will reveal which initiatives are the most reliable and would benefit the region under the uncertainty of future conditions [19, 20].

The resilience register methodology is a mathematical framework used to prioritize initiatives based on how well they improve organizational performance metrics [21]. The resilience register combines qualitative analysis and scenario analysis, as well as quantitative comparisons to support strategic decision making with an emphasis on resilience [14, 22]. Scenario analysis is known to be an effective method for improving decision analysis, and the resilience register leverages this fact to enhance decision making and assess the influence of scenarios [23]. Additionally, the resilience register is iterative, allowing stakeholders to revise their input to initiatives, importance criteria, and scenarios based on results – a critical element of effective analysis of resilience [24].

A critical theme of logistics systems in the post-pandemic era is data science for addressing risk and uncertainty in decision-making of diverse stakeholders outside transportation agencies such as enterprise systems and communities. This report describes two innovations in infrastructure planning: a data science approach to complexity balanced modeling of freight modality diversion for truck and rail and expansion of modalities transportation planning and diversion modeling to enterprise and community risk management for resilience of risk-based decision-making modeling for evolving preferences of communities, enterprise, and other stakeholders. First, modality-diversion modeling is used by transportation agencies to assess the impacts on nearby infrastructure of increased capacity on an existing corridor. Many stakeholders are subject to risks from this diversion, but are not currently able to benefit from knowledge of diversions. Second, a framework for stakeholders to interpret modality diversion as risk to their interests are developed in an enterprise and community risk management model.

1.3 Organization of the Report

The report is divided into two major sections: methodology and results.

The methodology section introduces the resilience register methodology. This includes an overview which outlines the major objectives of the resilience register. The section also includes the four major steps required to execute the risk register. Step one is the collection of performance criteria and a set of initiatives. Step two is outlining emergent conditions and generating scenarios. Step three updating priorities under disruptive scenarios. Step four is quantifying the disruption to they system.

The results section presents four case studies. Case one uses the risk register to analyze projects from the Crater Economic Development Strategy report. Case two assesses the impacts of disruptive scenarios on the employers of the Crater region. Case three presents an analysis of supply chain assets in the Crater region using the risk register and the modality diversion model. Case four outlines an enterprise and community risk model for the Crater region.

These sections are followed by discussions, conclusions, and recommendations.

2 Methodology

2.1 Overview

The resilience register is a scenario-based preference framework used to identify exogenous conditions that are the most and least disruptive to a system. The resilience register outlines how organizational priorities changes due to the influence of scenarios such as a pandemic or a natural disaster [3]. To execute the resilience register, the analyst must compiles lists of performance criteria, initiatives, emergent conditions, and scenarios.

2.2 Step 1: Performance Criteria and Initiatives of the Region

Performance criteria are used to measure the impact of organizational decisions, such as the implementation of an initiative. The set of performance criteria $C = \{c_1, ..., c_k\}$ are derived from program analysis and literature reviews – for this report, the performance criteria are derived from the comprehensive economic development strategy developed by the CPDC [2]. The performance criteria used throughout this analysis can be found in Exhibit 2.

c_1: *quality of citizen's life* refers to the notion that an initiative improves the standard of living of the population – this could be increased wages, new jobs, new technologies, or enhanced amenities. c_2: *innovation* refers to the ability of an initiative to generate a new idea, technology, method, or product that may be beneficial to the region. c_3: *economic development* is the ability of an initiative to improve key economic metrics in the region such as new jobs, investment in infrastructure, or the creation of new partnerships leading to investment in the region. c_4: *region support and economic resilience* refers to how well an initiative insulates the region from fluctuations in economic conditions. If an initiative scores well for c_5: *carbon footprint*, this would indicate that the initiative reduces the region's impact on the environment. c_6: *affordability* refers to the cost of the initiative, if applicable. c_7: *sustainability* represents the ability of the initiative to meet current needs without negatively impacting future generations, especially with respect to the environment. c_8:

feasibility refers to how likely an initiative is to be completed – for example, it is unlikely the region could attract the headquarters of a major tech company, while it is likely the region could attract major manufacturing organizations. c_8: *safety* refers to the degree to which the initiative improves the safety of the local population.

Index	Criterion
c_1	Quality of Citizens' Life
c_2	Innovation
c_3	Economic Development
c_4	Region Support and Economic Resilience
c_5	Carbon Footprint
c_6	Affordability
c_7	Sustainability
c_8	Feasibility
c_9	Safety
c_i	Others

Exhibit 2: Performance criteria for industrial supply chains of the Crater region [2]

Initiatives are a set of technologies, policies, assets, or projects that an organization controls. The set of initiatives $X = \{x_1, ..., x_n\}$ is gathered from stakeholders and through elicitation from experts. In a resilience register analysis, performance criteria are used to rank initiatives. The degree to which an initiative will address performance measures determines how highly the initiative will rank when compared to alternatives. When exposed to disruptive scenarios, the ability of an initiative to influence performance criteria may be reduced. Initiatives are re-ranked under each scenario. The list of performance criteria is not exhaustive and can be adapted based on stakeholder input to meet changing needs.

As an example, the success criterion for the CPDC includes *quality of citizen's life*, *economic development*, and *feasibility*. Potential initiatives may include *improvements to a critical roadway* and *attracting industrial manufacturers to the region*. Improvements to a roadway would have a high impact on quality of life, a moderate impact on economic development, and a high feasibility. Conversely, attracting new manufacturers to the region would have a high impact on quality of life, a high impact on economic development, and moderate feasibility. The resilience register is able to determine the rank initiatives based on how well each initiative addresses the criteria.

2.3 Step 2: Emergent Conditions and Scenarios of the Region

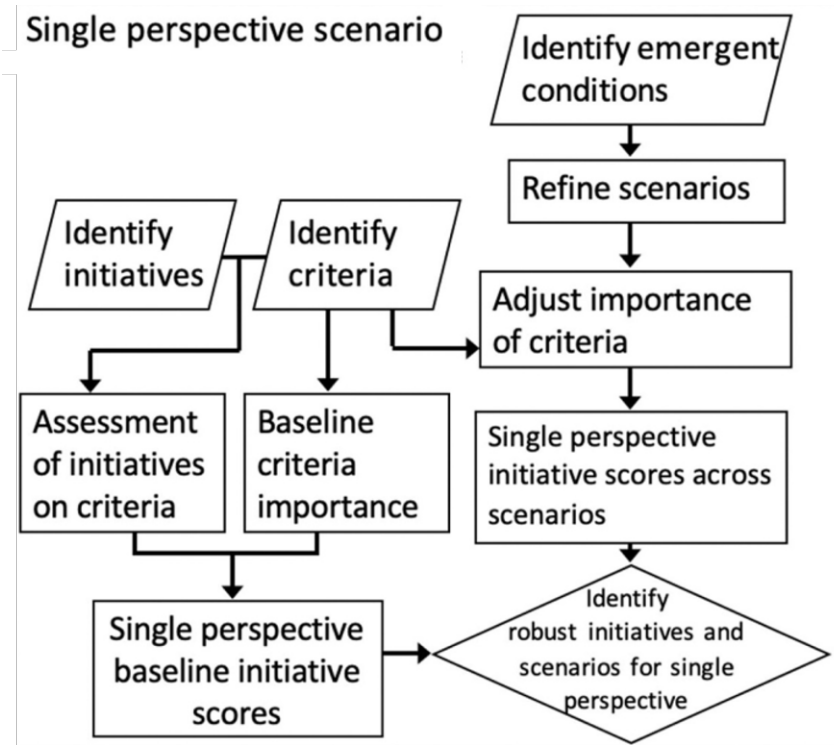


Exhibit 3: Overview of the resilience register methodology used to study industrial supply chains of the Crater region [3]

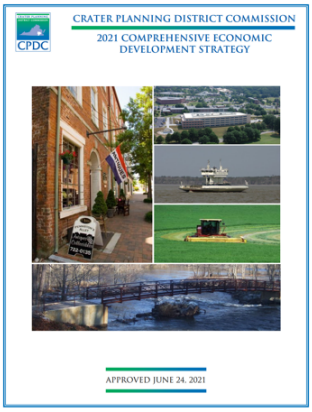
Emergent conditions are potential events that could impact how an initiative is evaluated. The set of emergent conditions $E = \{e_1, ..., e_i\}$ is derived from stakeholder input and analysis of third-party resources. Typically, emergent conditions are events that disrupt system performance and threaten the efficacy of initiatives. Emergent conditions are consolidated into a set of scenarios $S = \{s_1, ..., s_k\}$, which consist of one or more emergent conditions. Each of these scenarios is contrasted with the *baseline* scenario, in which no emergent conditions occur. As an example, some potential emergent conditions for the Crater regions are *population decrease* and *flooding*. Population decrease may fall into both the *natural disaster* and *pandemic* scenarios, while flooding would fall only into the natural disaster scenario. The sets of emergent conditions and scenarios used for this report can be found in Exhibits 4 and 6. The set of scenarios and associated emergent conditions can be found in Exhibit 7. The impact each scenario has on priorities can be found in Exhibit 8.

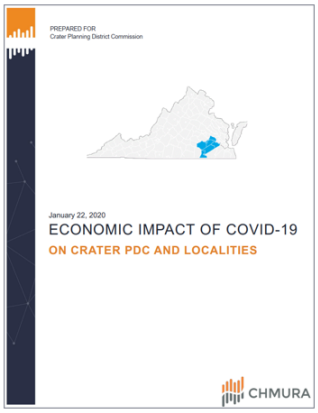
Index	Emergent Condition
e_1	Social Distancing Requirements
e_2	Fiscal Stress
e_3	Lack of Infrastructure
e_4	Lack of Higher-Skilled, Well-Trained Workforce
e_5	Reduced Regional Cooperation
e_6	Poor Health Indicators
e_7	Funding Decrease
e_8	Flooding
e_9	Changes to Economic Systems
e_{10}	Category 5 Hurricane
e_{11}	Decreased Social Cohesion
e_{12}	Multiple Super Storms in Same Season
e_{13}	Increased Operational Costs
e_{14}	Increased Public Emphasis on Carbon Emissions
e_{15}	Decrease in Total Labor Productivity
e_{16}	Drought
e_{17}	Population Increase
e_{18}	Population Decrease
e_{19}	Social Unrest
e_{20}	Network Damage due to Cyber Attack
e_{21}	Ransomware Attack
e_{22}	Data Leak
e_{23}	Decreased Security of Vital Infrastructure
e_{24}	Destruction of Infrastructure
e_i	Others

Exhibit 4: Emergent conditions for industrial supply chains of the Crater Region

Emergent Conditions

- The set of emergent conditions are derived from academic literature, the 2021 Comprehensive Economic Development Strategy, and other CPDC resources





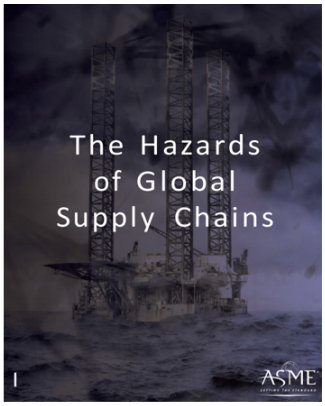


Exhibit 5: Sources used to identify emergent conditions that may impact supply chains in the Crater region

Index	Potential Scenario
s_1	Funding Decrease
s_2	Natural Disaster
s_3	Pandemic
s_4	Increased Environmental Regulation
s_5	Climate Shift
s_6	Green Technology Movement
s_7	Cyber Security Attack
s_i	Others

Exhibit 6: Scenarios for the Crater Region

Exhibit 7: Scenarios are comprised of one or more emergent conditions. This figure shows which emergent conditions make up each of the seven scenarios for industrial supply chains of the Crater region.

p.01 Crater PDC	s.01 - Funding Decrease	s.02 - Natural Disaster	s.03 - Pandemic	s.04 - Increased Environmental Regulation	s.05 - Climate Shift	s.06 - Green Technology Movement	s.07 - Cyber Security Attack
c.01 - Quality of Citizens' Life	-	-	Increases	-	-	-	-
c.02 - Innovation	Increases	-	-	Increases Somewhat	Increases	Increases	-
c.03 - Economic Development	Decreases Somewhat	Decreases Somewhat	Decreases	-	-	Increases Somewhat	-
c.04 - Region Support and Economic Resilience	Increases	-	Decreases Somewhat	-	Increases Somewhat	-	Increases Somewhat
c.05 - Carbon Footprint	-	Increases	Decreases	-	Increases Somewhat	Increases	Decreases
c.06 - Affordability	Increases	Increases Somewhat	Increases Somewhat	-	Decreases Somewhat	Decreases Somewhat	-
c.07 - Sustainability	-	-	Increases	-	Increases	Increases Somewhat	-
c.08 - Feasibility	Increases Somewhat	Increases	-	-	Decreases Somewhat	-	Decreases
c.09 - Safety	-	-	Increases	-	Increases	Increases Somewhat	Increases

Exhibit 8: When scenarios disrupt a system, the relative importance of performance criteria may rise or fall based on which elements of a system are impacted. This figure outlines how criteria valuation changes under each disruptive scenario for the Crater region.

Returning to the previous example, consider the hypothetical *improvements to a critical roadway* and *attracting industrial manufacturers to the region* initiatives. Under the baseline scenario, attracting manufacturers may be the preferred initiative. However, under the *natural disaster* scenario, the attracting manufacturers initiative may fail to influence *feasibility* criterion as potential manufacturers look elsewhere. Given this, the roadway improvements initiative may rise in priority. It should be noted that the success criteria, emergent conditions, and scenarios will remain constant throughout this report. However, the set of initiatives will change across analyses of Crater projects, employers, and logistics assets.

2.4 Step 3: Updating Priorities for Supply Chains of the Region

After performance criteria, initiatives, emergent conditions, and scenarios have been collected, this information is entered into the resilience register. The next step is to assess to what degree an initiative addresses each criterion. The available levels are *strongly agree, agree, somewhat agree*, and *neutral*. That is, some initiatives may not address every criterion. Scores are recorded in the impact matrix X_i, where the score initiative x_i receives for criterion c_j is entered as x_{ij}. Each initiative is given a score for each scenario as shown in Equation 1, where X is the impact matrix and W is the vector of scenario impact scores.

$$V(x_i)_k = W_k X_i \tag{1}$$

The initiatives can be ranked as in 2, where $\succ$ indicates that x_i is ranked higher than x_j.

$$IF\, V(x_i)_j > V(x_j)_k\, THEN\, x_i \succ x_j \tag{2}$$

These results can now be used to determine organizational priorities. Extending the hypothetical from above, a decision maker may choose to invest in attracting manufacturers to the region in the baseline scenario. However, if there is reason to believe a natural disaster scenario is likely, the decision maker may prefer to improve the resilience of roadways.

While this information is useful for determining organizational priorities, aggregating the impact of scenarios on initiatives provides critical information for enterprise risk analysis. This information is called *disruptiveness*, a measure of how influential a scenario is on the system as a whole.

2.5 Step 4: Quantifying Disruption and Resilience of the Region

After initiatives are scored for each scenario, they are ranked as $R(x_i)_k$, or the rank of each initiative x_i under scenario s_k, including the baseline. Using these values, the register derives the disruptiveness measure $D(s_k)$.

$$D(s_k) = \sum_{i=1}^{n} (R(x_i)_b - R(x_i)_k)^2 \tag{3}$$

The disruptiveness scores are then normalized such that they fall on a scale of 0-100, which in turn identify which scenarios are the most disruptive to the system. A high disruptiveness score indicates that a given scenario poses a greater threat to the system than lower-scoring scenarios. Such

information can alert an organization to inform future actions and activity. Using the hypothetical example, assume that the *natural disaster* scenario is the most disruptive. The CPDC may then favor projects that increase the resilience of the region with respect to damage caused by natural disasters. Further, once the most disruptive scenarios have been identified, the resilience register process can be repeated to refine organizational priorities and reduce the impact of disruptive scenarios.

2.6 Summary and Next Steps

This section outlined the step required to execute the resilience register methodology. This includes several of the required inputs such as the set of performance criteria, emergent conditions, and scenarios. Further, this sections outlines how performance criteria change under each disruptive scenario.

Initiatives will be included in the following section which discusses the results. There are three sets of initiatives use in the analyses in the following section – a set of projects from the CEDS report, a set of many of the largest employers in the Crater region, and a set of major logistics assets in the region. For each set of initiatives, the following section describes how priorities change under various disruptive scenarios. These changes are aggregated to determine which scenarios are most disruptive to the region.

3 Results

3.1 Overview

The following analysis implements the resilience register methodology for three aspects of the economy in the Crater region – CPDC projects, major regional employers, and regional logistics assets. There is overlap across each aspect, however. For example, a roadway improvement may be in both the Crater projects and logistics asset analysis. Further, a specific company or organization may be included in the employer and logistics analysis. The report is divided to simplify comparisons between assets. For example, it is not logical to compare the relative value of a potential project (such as the value gained by renovating a roadway) with an existing asset (the existing value added by a prominent warehouse). However, the focus of this report is not to rank or prioritize projects or assets, but to identify the impacts of disruptions to supply chains and to the Crater region as a whole. Separating the analysis into parts enables the CPDC to isolate how different disruptive scenarios will impact different segments of the region.

3.2 Case 1: Crater Economic Development Strategy

The project priority list is a set of twenty-one prioritized projects that benefit members of the Crater PDC. The projects receive funding from a variety of sources including state, federal, and private entities. With few exceptions, the project implementation timeline and costs are known, as well as the agency responsible for executing the project. The set of prioritized projects can be found in Exhibit 9. The assessment of initiatives and their affect on criteria can be found in Exhibit 10.

Index	Initiative
x_1	MAMaC 1,600 Acre Mega Site
x_2	Sussex County Route 626 1,500 Acre Mega Site
x_3	Global Logistics Park
x_4	I-95 / I-85 Interchange Improvements
x_5	Appomattox River Dredging Project
x_6	Redevelopment of Exit 52 on I-95 (City of Petersburg Gateway)
x_7	Crater Small Business Development Center
x_8	Crater Procurement Technical Assistance Center
x_9	Improvements to Existing U.S. Route 460
x_{10}	Raw water intake and waterline to Roxbury Area of Charles City County
x_{11}	Grey's Creek Marina Project, public access to James River
x_{12}	Route 602 (Cabin Point Road) Industrial Park - 134 Acres
x_{13}	Water Line Extension - Mega Site
x_{14}	Dendron Area Water System Replacement
x_{15}	Route 36 Regional Corridor Revitalization Project
x_{16}	Halifax Industrial Park Site Improvements (one site)
x_{17}	Business Incubator Collocated With Southside Virginia Educational Center
x_{18}	Claremont Water System Improvements
x_{19}	Stony Creek Wastewater Treatment Plant Upgrade
x_{20}	Tri-Cities Area Business Incubator
x_{21}	New Industrial Property - 38 Acres
x_i	Others

Exhibit 9: Prioritized set of initiatives outlined by the CPDC in the 2020-2021 Crater Economic Development Strategy [2]

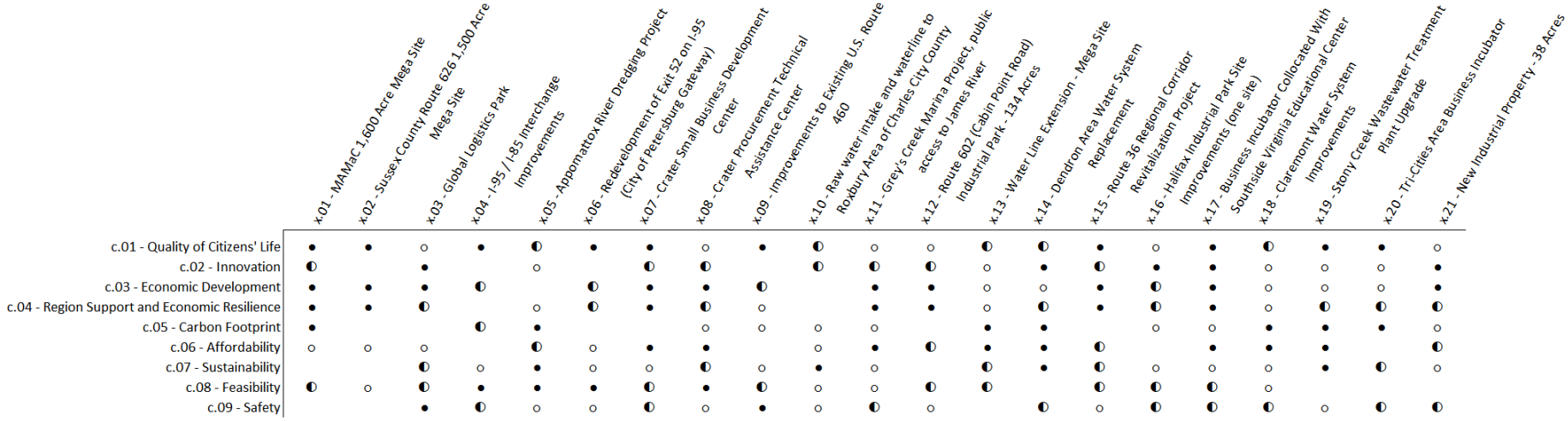


Exhibit 10: Assessment of initiatives against criteria used for the prioritization of initiatives for enterprise risk analysis of Crater projects. Strongly agree is represented by a filled circle, agree is represented by a half filled circle, somewhat agree is represented by an unfilled circle, and neutral is represented by a dash.

Using this list of projects as the set of initiatives, the resilience register visualizes how project priorities can change under various disruptive scenarios as seen in Exhibit 11. The black vertical line on each bar in the chart represents the ranking of the initiative under the baseline scenario. The red segment (extending to the left of the black vertical line) of each bar represents how far an initiative may fall in rank under various scenarios. Conversely, the blue segment (which extends to the right of the black vertical line) of each bar shows how high an initiative may rise. Generally, if the baseline ranking is centered on the bar, then that initiative is not ranked consistently among any of the disruptive scenarios. An example of this can be seen in Exhibit 11, with initiative x_3: *global logistics park*. If the baseline falls toward the left edge of the bar, then the initiative tends to decrease in rank under various scenarios and may not be an ideal candidate for implementation. Initiative x_7: *Crater small business development center* is one example of such an initiative. If the baseline falls on the right edge of the bar, the initiative is likely to improve in ranking for various scenarios and may make the the project more attractive. Initiative x_6: *redevelopment of exit 52 on I-95 (City of Petersburg Gateway)* is one such initiative – although it ranks twentieth in the baseline scenario, in the right conditions it could rise to position five. This indicates that the project is highly resilient, and is still a candidate for development despite its low ranking under the baseline scenario.

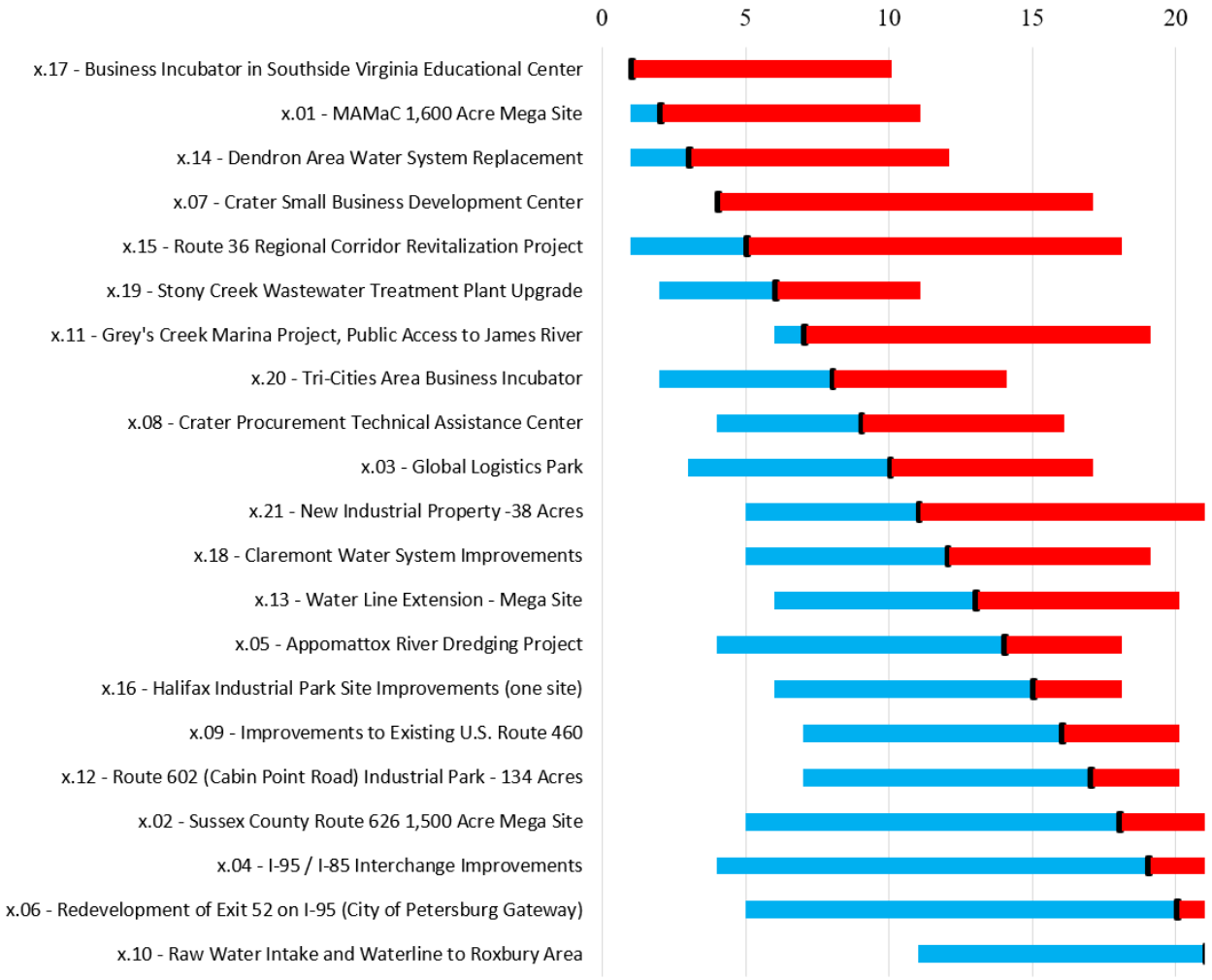


Exhibit 11: Results of the resilience register methodology for Crater PDC projects. The black line represents the ranking of the initiative in the baseline scenario. The red bar (extending right of the black line) represents how far an initiative may fall in rank under various scenarios. The blue bar (extending left of the black line) shows how high an initiative may rise under various scenarios.

The highest rated initiative, x_{17}: *business incubator in southside Virginia educational center*, is the preferred initiative under the baseline scenario. However, it may fall as low as the tenth rated initiative under the right conditions. Contrast this initiative with x_1: *MAMaC 1,600 acre mega site*. While x_1 ranks second in the baseline scenario, and could rank as low as eleventh, it was was given the highest priority prior to the resilience register analysis. Though further assessment is required, perhaps x_1 would still provide more value to the CPDC.

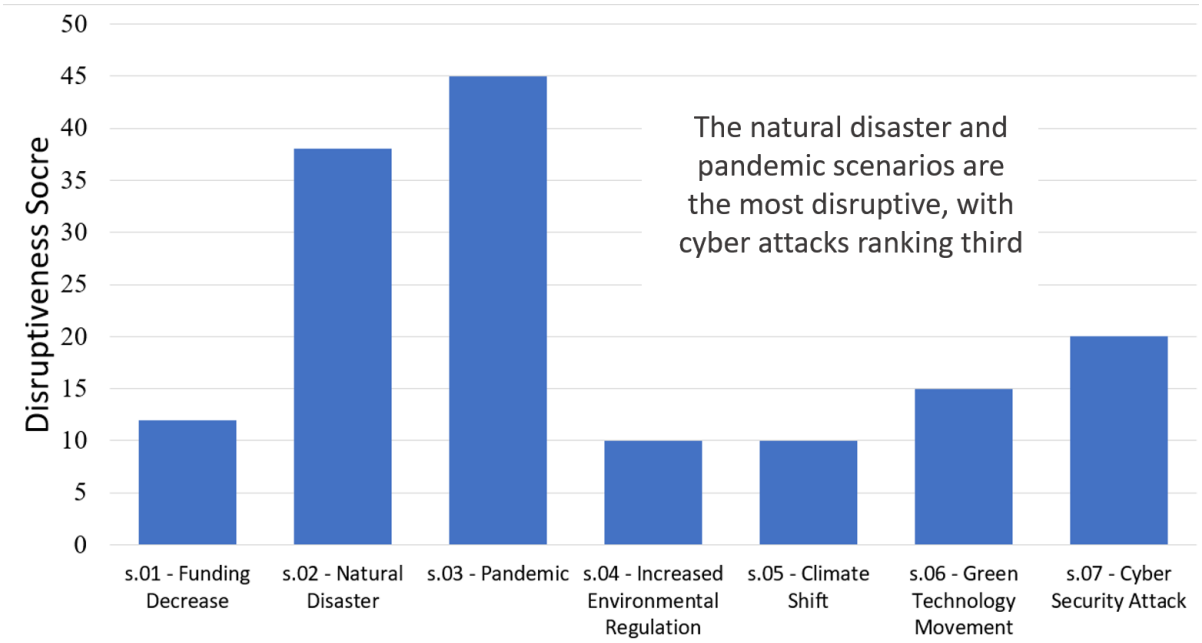


Exhibit 12: Normalized disruptiveness score for each scenario using Crater PDC projects

Though many of the initiatives listed in Exhibit 9 are already in progress, observing how priorities change under various scenarios is still a useful exercise for enterprise risk analysis. Consider Exhibit 12, which expresses the normalized disruptiveness score for each scenario in Exhibit 6. A high disruptiveness score indicates that the scenario has a large impact on the prioritization of initiatives and on the system at large. This analysis indicates that the two most disruptive scenarios are s_2: *natural disaster* and s_3: *pandemic*. That is, a scenario such as the COVID-19 pandemic that requires social distancing is highly disruptive to initiatives such as x_{17}: *business incubator in southside Virginia educational center*. A pandemic scenario may delay infrastructure improvement projects and reduce the efficacy of business development programs. Additionally, natural disasters can disrupt physical infrastructure that prevents the movement of people and goods, make roads or buildings unsafe, or cause some of the population to leave the region. When contrasted with the other scenarios, this analysis indicates that events which cannot be predicted in the long-term (such as a pandemic or natural disaster) tend to be more disruptive than events that can be foreseen (a funding decrease or climate change).

A notable exception to this is the the s_7: *cyber security attack* scenario. While not as disruptive as the top two scenarios, a cyber attack still has an impact on CPDC project priorities. A ransomware attack such as the one that affected the Colonial Pipeline has the potential to disrupt any of the projects [25]. A successful attack may result in lost data, the inability to perform normal business operations, or damage to the network. However, when compared to natural disasters and pandemics it is relatively easy for the region to recover from a cyber attack. Such an attack is likely to be isolated to a single organization and is unlikely to cause irreversible damage to infrastructure.

3.3 CASE 2: EMPLOYERS OF THE CRATER REGION

The list of thirty of the largest employers of the Crater region can be found in Exhibit 13. These employers provide jobs for Crater citizens as well as services and amenities to the region. The government sector is the largest employer in the region. This includes Department of Defense, school, city, and county employees. Additionally, the Greensville Correctional Center and Sussex I Correctional Center are among the largest employers in the region. The assessment of initiatives and their affect on criteria can be found in Exhibit 14.

Index	Initiative
x.01	US Department of Defense
x.02	Wal-Mart
x.03	County of Prince George
x.04	Dominion Energy
x.05	Central State Hospital
x.06	Boar's Head Provisions Co.
x.07	Integrity Staffing Solutions
x.08	Greensville Correctional Center
x.09	AdvanSix, Inc.
x.10	City of Petersburg
x.11	City of Petersburg School Board
x.12	Hopewell City School Board
x.13	Dinwiddie County School Board
x.14	HCA Virginia Health System
x.15	Food Lion
x.16	Good Neighbor Holdings LLC
x.17	Colonial Heights School Board
x.18	Cantu Services Inc
x.19	Delhaize America Distribution Center
x.20	US Department of Justice
x.21	Virginia Department of Transportation
x.22	Amazon Fulfillment Service Inc.
x.23	City of Hopewell
x.24	Perdue Products
x.25	Con Secours Southside Regional Medical Center
x.26	Gerdau
x.27	Greensville County School Board
x.28	DuPont Specialty Products
x.29	Amstead Rail Company
x.30	Sussex I Correctional Center
x.i	Others

Exhibit 13: List of thirty of the largest employers in the Crater region

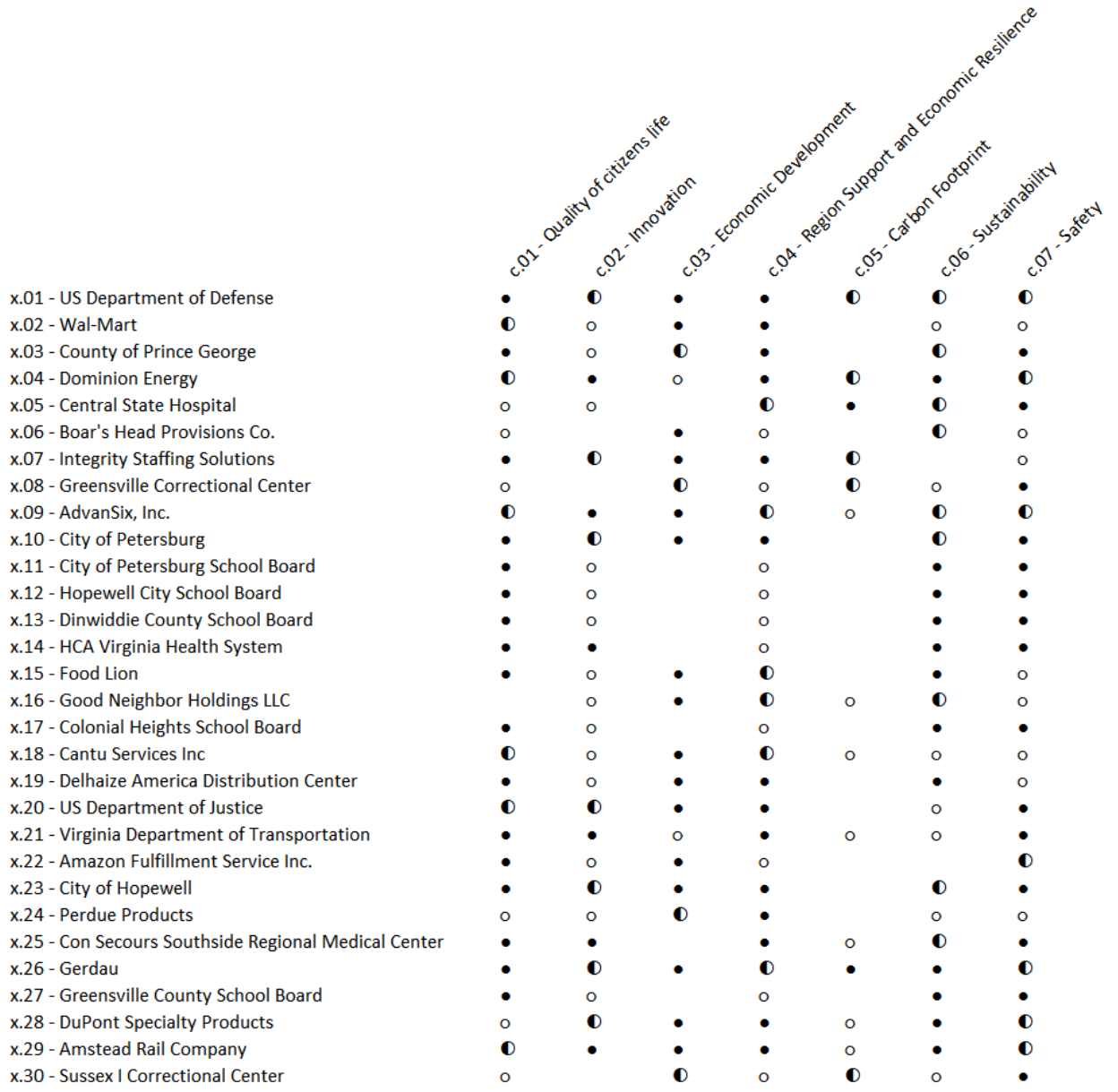


Exhibit 14: Assessment of initiatives against criteria used for the prioritization of initiatives for enterprise risk analysis of Crater Region employers. Strongly agree is represented by a filled circle, agree is represented by a half filled circle, somewhat agree is represented by an unfilled circle, and neutral is represented by a dash

When examining disruptiveness scores using Crater projects in Exhibit 12, s_2: *natural disaster* and s_3: *pandemic* were the most disruptive, and induced a fairly similar level of disruption at thirty-eight and forty-five respectively. Contrast these results with the analysis of employers in the Crater region in Exhibit 15. While the s_2: *natural disaster* and s_3: *pandemic* scenarios remain the most disruptive, the gap between the two widens from seven for the Crater projects to thirteen in the employment analysis. That is, the pandemic scenario is relatively more disruptive to employment than to regional project priorities. This follows, as employers are reliant on the movement of the local population which is significantly hampered by a pandemic. Additionally, the region is impacted by reduced employer efficacy in two facets – the loss of local jobs or wage reduction, and the inability of an organization to provide services to the Crater region.

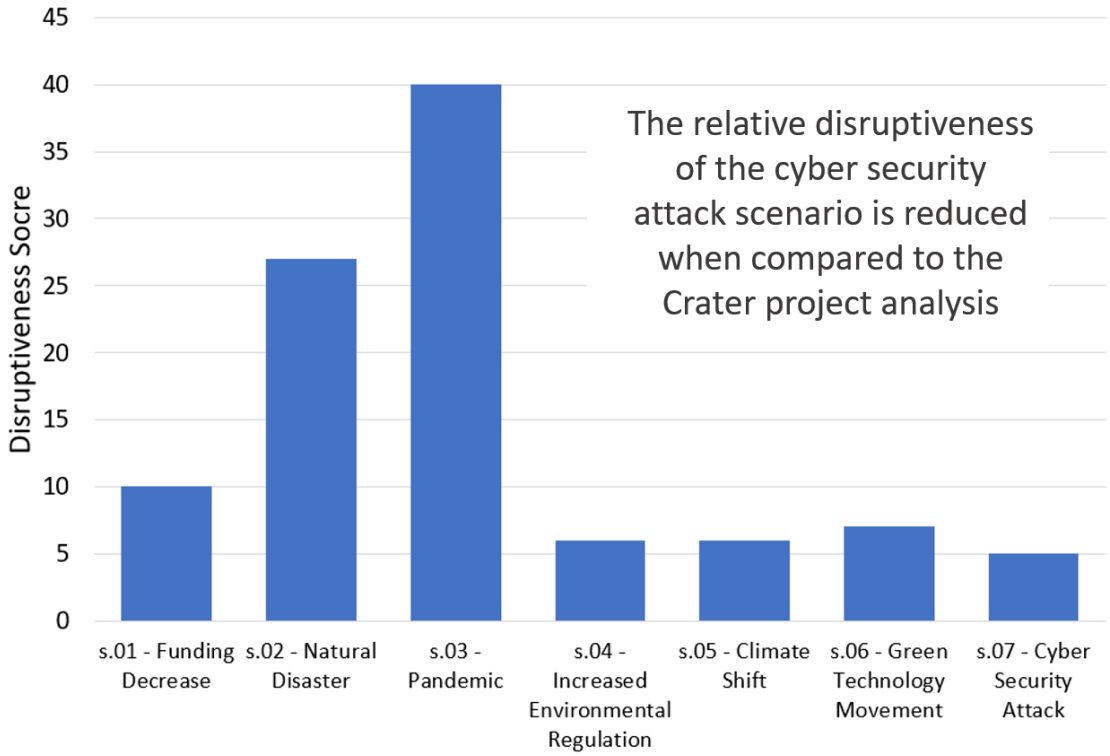


Exhibit 15: Normalized disruptiveness score for each scenario using thirty of the largest employers of the Crater region

The influence of scenarios on employers can be seen in Exhibit 16. As these are established organizations rather than projects as in the previous analysis, results should be interpreted slightly differently. Rather than representing how priorities change under disruptive scenarios, this analysis describes how the ability of an organization to impact performance criteria changes under different scenarios. For example, Exhibit 16 shows that schools are ranked relatively low in the baseline – that is, schools do not contribute significantly to improving performance criteria under the baseline scenario. However, in a pandemic scenario, the importance of schools rises greatly. When schools close, parents are forced to find alternative daytime child care, perhaps preventing a parent from working. In a pandemic, it is critical that schools are able to remain open to minimize the impact to the community. This analysis indicates that dedicating resources to ensuring schools

can remain open safely – such as promoting vaccinations for eligible populations, universal indoor masking, screening, and social distancing – can add to the resilience of the Crater region [26].

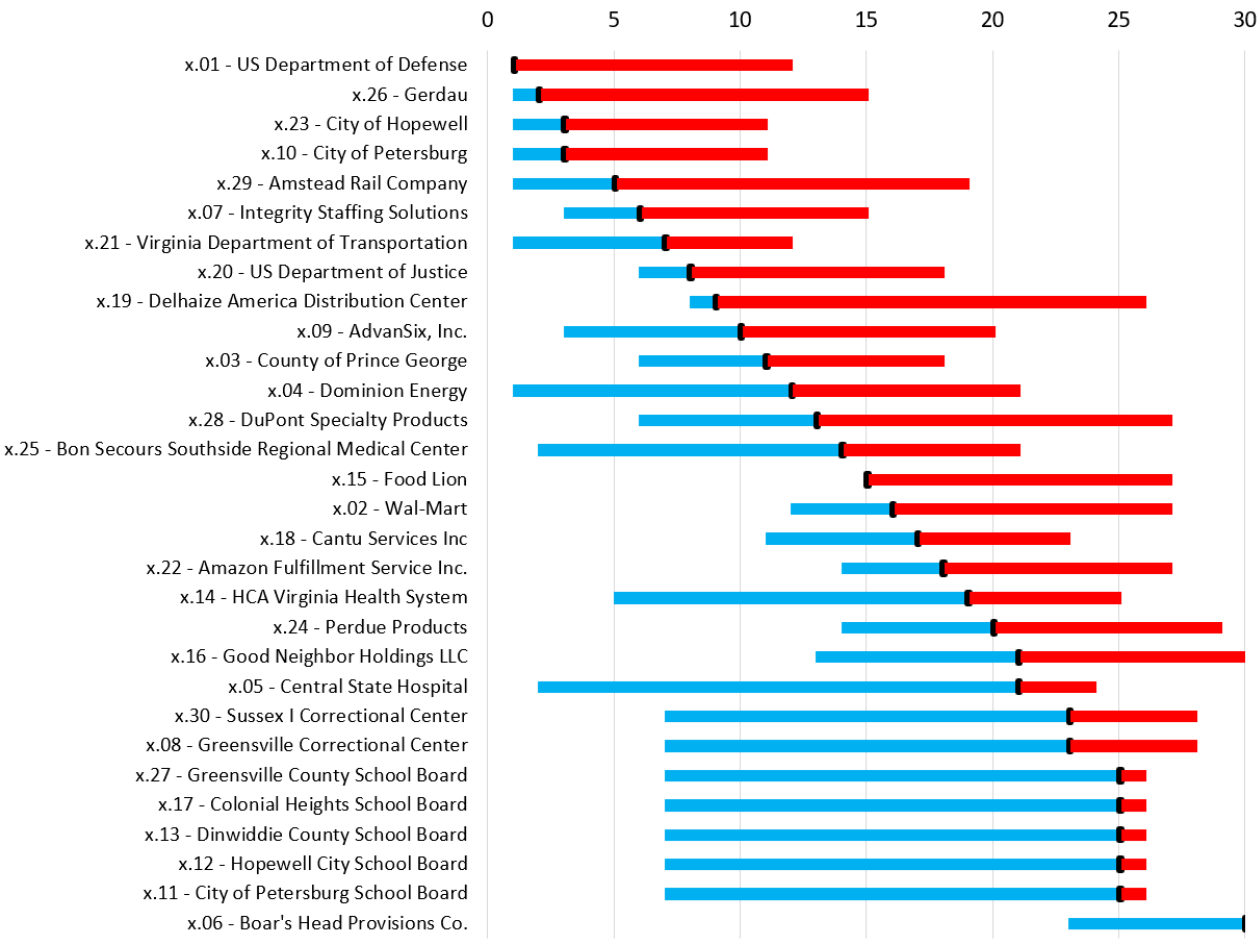


Exhibit 16: Results of the resilience register methodology for thirty of the largest employers of the Crater region. The black line represents the ranking of the initiative in the baseline scenario. The red bar (extending right of the black line) represents how far an initiative may fall in rank under various scenarios. The blue bar (extending left of the black line) shows how high an initiative may rise under various scenarios.

This is not to say that the second most disruptive scenario, s_2: *natural disaster*, is not influential. For example, the ranking of x_4: *Dominion Energy* has one of the largest ranges from the highest to lowest potential rankings, ranging from first to twenty-first. In the natural disaster scenario, ensuring that the region maintains electric power is critical for support and recovery services to function. Similarly, x_{25}: *Bon Secours Southside Regional Medical Center* and x_{14}: *HCA Virginia Health System* are moderately ranked in the baseline scenario, but become extremely valuable in a natural disaster scenario, as large medical facilities will receive an influx of injured patients in a short time period.

3.4 Case 3: Supply Chain Assets of the Crater Region

Logistics assets such as warehouses, distribution facilities, roads, ports, and utilities are critical elements of industry supply chains. The set of such assets that service the Crater region can be found in the map in Exhibit 17. Assessing the impact of disruptions on logistics systems is two-fold: first, this report uses the resilience register methodology to identify the most disruptive scenarios, and observe how asset priorities change under these scenarios. Second, modal diversion model highlights how logistics systems changes when exposed to disruptive events.

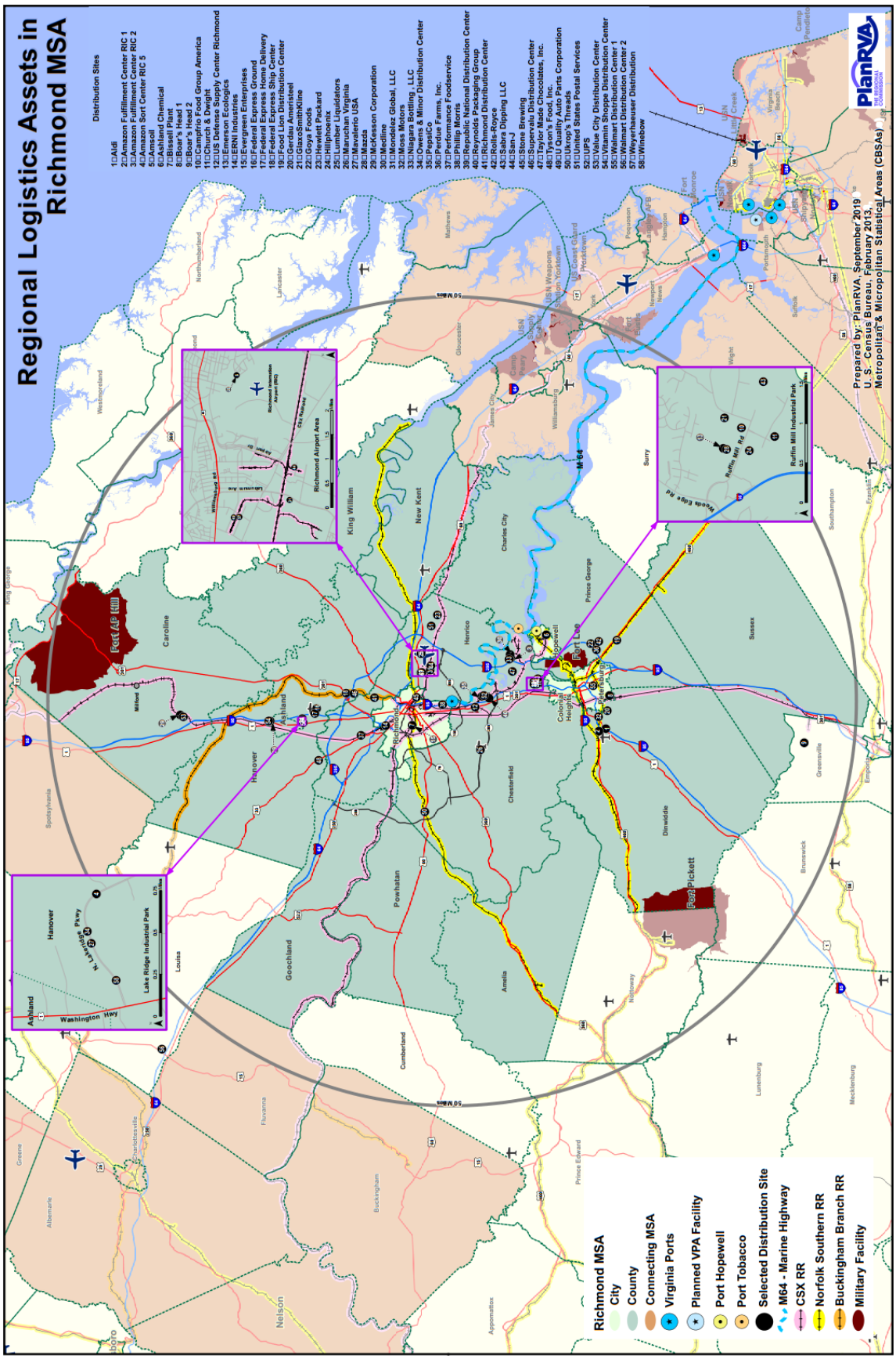


Exhibit 17: Map of major logistics assets that service the Crater region

3.4.1 Resilience Register

The set of logistics assets are outlined in Exhibit 18. The list includes twenty-four major commercial and government distribution hubs, eight major roads, two major railroads, two major port assets, and five utility services. It should be noted that several similar assets have been combined when appropriate. For example, several Virginia Water and Waste Authorities service the Crater region such as the Dinwiddie County Water Authority and Sussex Service Authority. Further, the Appomattox River Water Authority serves several member municipalities. With respect to the resilience register analysis, the impact of disruptions to logistics systems would be similar were any of these services to fail. The relationship between success criteria and the logistic assets initiatives can be found in Exhibit 20.

Index	Initiative	Index	Initiative
x.01	Amazon Fulfillment Centers	x.23	Moss Motors
x.02	Walmart Distribution Centers	x.24	Port Hopewell
x.03	UPS	x.25	Norfolk Southern RR
x.04	Aldi	x.26	CSX RR
x.05	Perdue Farms	x.27	M-64 Marine Highway
x.06	Food Lion Distribution Center	x.28	Fort Lee
x.07	Boar's Head	x.29	Fort Pickett
x.08	GlaxoSmithKline	x.30	Ukrop's Threads
x.09	Defense Supply Center Richmond	x.31	I-295
x.10	Sabra Dipping LLC	x.32	I-95
x.11	Reynolds Packaging Group	x.33	I-64
x.12	PepsiCo	x.34	I-85
x.13	Maruchan Virginia	x.35	Route 58
x.14	Medline	x.36	Route 10
x.15	Campfrio Food Group America	x.37	Route 288
x.16	Mazda	x.38	Route 460
x.17	Goya Foods	x.39	Internet Services
x.18	Ashland Chemical	x.40	Waste Management
x.19	Church & Dwight	x.41	Power Grid
x.20	Hill Phoenix	x.42	Water Management
x.21	Gerdau Ameristeel	x.43	Telecommunication
x.22	Emerson Ecologics	x.i	Others

Exhibit 18: List of major logistics assets that service the Crater region

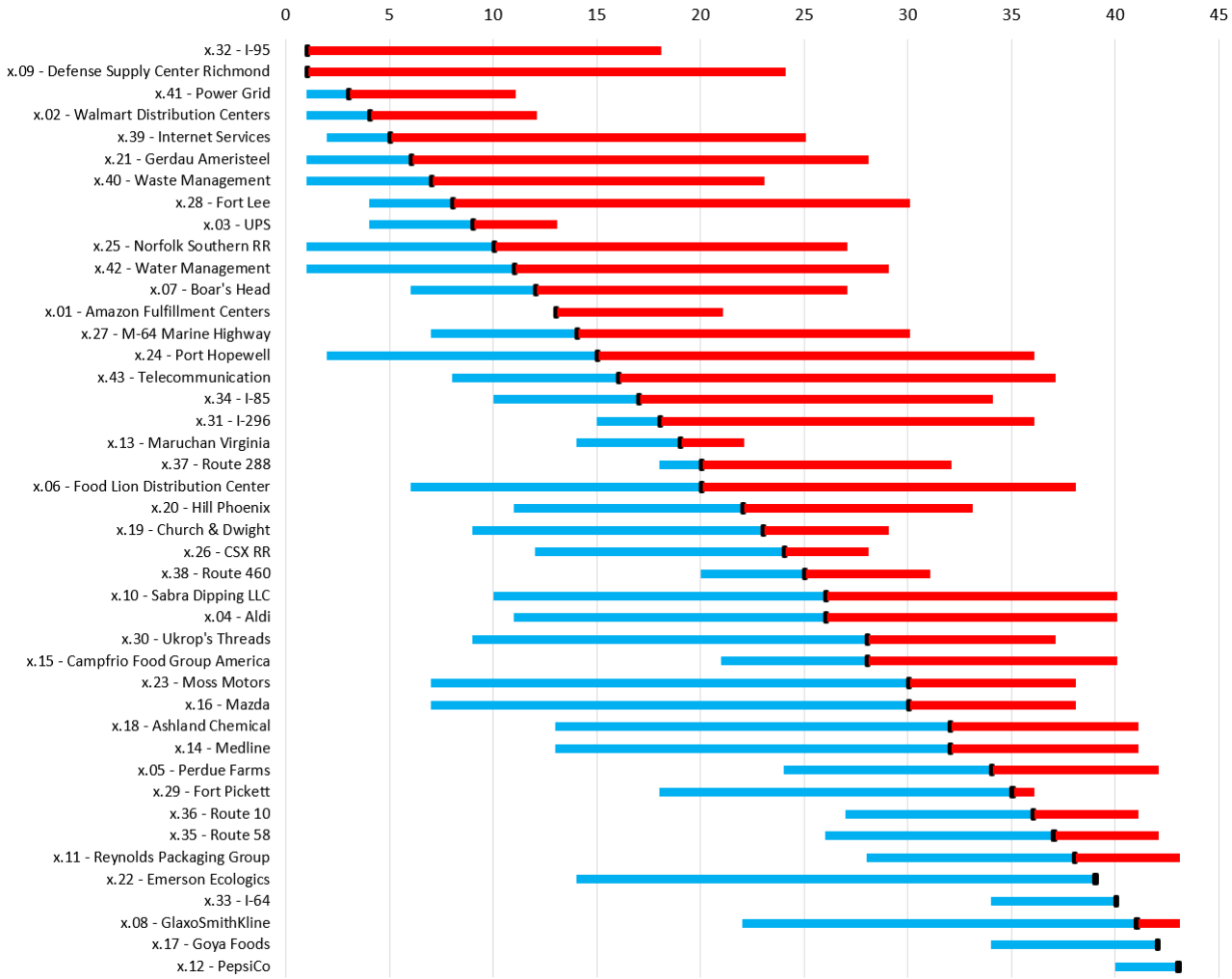


Exhibit 19: Results of the resilience register methodology for the logistics assets of the Crater region. The black line represents the ranking of the initiative in the baseline scenario. The red bar (extending right of the black line) represents how far an initiative may fall in rank under various scenarios. The blue bar (extending left of the black line) shows how high an initiative may rise under various scenarios.

	c.01 - Quality of Citizens Life	c.02 - Innovation	c.03 - Economic Development	c.04 - Region Support and Economic Resilience	c.05 - Carbon Footprint	c.06 - Sustainability	c.07 - Safety
x.01 - Amazon Fulfillment Centers	◐	○	◐	◐	○	○	○
x.02 - Walmart Distribution Centers	●	○	◐	●	○	○	○
x.03 - UPS	●	◐	○	◐	◐	○	○
x.04 - Aldi	●	○	○	○		◐	
x.05 - Perdue Farms	◐		○	◐		○	
x.06 - Food Lion Distribution Center	●		○	◐		○	○
x.07 - Boar's Head	◐	○	◐	●	○		
x.08 - GlaxoSmithKline	○			○	○	○	◐
x.09 - USDC Richmond	●	◐	◐	●	○	◐	
x.10 - Sabra Dipping LLC	○		◐	○	●	◐	
x.11 - Reynolds Packaging Group	○		◐		○	○	○
x.12 - PepsiCo	○		○	○		○	
x.13 - Maruchan Virginia	◐	○	○	◐	◐	○	
x.14 - Medline	◐	○	○		○	○	◐
x.15 - Campfrio Food Group America	◐	○	○	◐		○	
x.16 - Mazda	○		○	◐	●	○	
x.17 - Goya Foods	○		○	○			○
x.18 - Ashland Chemical	◐	○	○		○	○	◐
x.19 - Church & Dwight	◐	◐	○	◐	○		
x.20 - Hill Phoenix	◐	◐	○	○	◐	◐	
x.21 - Gerdau Ameristeel	●	◐	◐	○	●	●	
x.22 - Emerson Ecologics	○	○		○	◐		○
x.23 - Moss Motors	○		○	◐	●	○	
x.24 - Port Hopewell	○	◐	◐	●	○	○	
x.25 - Norfolk Southern RR	○	○	◐	●	○	◐	◐
x.26 - CSX RR	○	○	○	◐	○	○	◐
x.27 - M-64 Marine Highway	○	○	◐	●	○	○	○
x.28 - Fort Lee	◐	○	●	●			○
x.29 - Fort Pickett	○	○	○	◐			○
x.30 - Ukrop's Threads	○		○	●	○	○	
x.31 - I-296	◐		◐	○	○	◐	◐
x.32 - I-95	◐		●	●	○	◐	◐
x.33 - I-64	○		○	○		○	○
x.34 - I-85	◐		◐	○	◐	◐	○
x.35 - Route 58	○		○	○	◐	○	
x.36 - Route 10	○		○	◐	○	○	
x.37 - Route 288	◐		◐	◐	○	○	
x.38 - Route 460	◐		○	◐	◐	○	
x.39 - Internet Services	●	◐	●	◐	○	○	
x.40 - Waste Management	●	○	○	◐	○	◐	●
x.41 - Power Grid	●	○	◐	◐		○	
x.42 - Water Management	●	○	○	○	◐	●	◐
x.43 - Telecommunication	●	◐	○	◐		○	

Exhibit 20: Assessment of initiatives against criteria used for the prioritization of initiatives for enterprise risk analysis of Crater region logistics assets.

Exhibit 19 shows how initiative priorities change under various scenarios. Consider x_{32}: *I-95*, the highest ranked initiative and x_{33}: *I-64*. Both initiatives are major highways that service the Crater region. However, I-64 does not fall within the borders of the CPDC member jurisdictions. As such, scenarios that impact I-64 have a lesser influence on the region than scenarios that impact I-95. It should be noted that eight initiatives can potentially rank first – x_{32}: *I-95*, x_9: *USDC Richmond*, x_{41}: *power grid*, x_2: *Walmart distribution centers*, x_{21}: *Gerdau Ameristeel*, x_{40}: *waste management*, x_{25}: *Norfolk Southern Railroad*, and x_{42}: *water management*. Note that of these eight, four are utilities services. Further, x_{39}: *internet services* can reach as high as the second ranked initiative. Utilities are critical elements of the logistics infrastructure in the Crater region, and their importance only increases under various disruptive scenarios.

Other initiatives of note include food distribution locations such as x_2: *Walmart distribution centers*, x_6: *Food Lion distribution center*, and x_4: *Aldi*. These assets are distributed throughout the baseline ranking, but each have the potential to rise by several positions. While other distribution centers are important for local commerce, the grocery distributors also provide food for the region – in a natural disaster scenario, it is critical to continue to provide food to the region. This case holds for the pandemic scenario as well – with social distancing requirements in effect and reduced access to alternative food sources, grocery stores become more critical to region stability. Consider the US Military assets, x_9: *Defense Supply Center Richmond*, x_{28}: *Fort Lee*, and x_{28}: *Fort Pickett*. The Defense Supply Center Richmond and Fort Lee both rank in the top 10 initiatives under the baseline scenario, while Fort Pickett ranks lower (though note that Fort Pickett is only partially contained in CPDC borders).

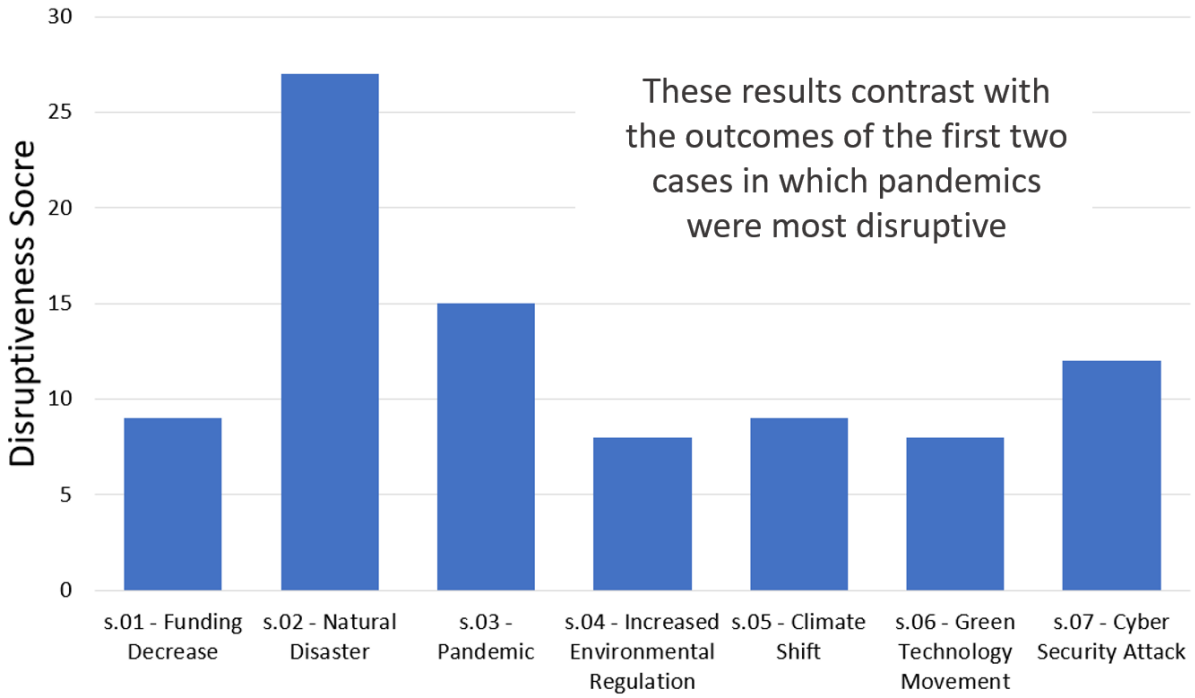


Exhibit 21: Normalized disruptiveness score for each scenario using the logistics assets of the Crater region

Contrasted with Exhibits 12 and 15, Exhibit 21 shows that the s_2: *natural disaster* scenario is the most disruptive. Natural disasters have the potential to damage infrastructure such as roads or rail, increasing the need to build resilient transportation vectors. Further, natural disasters can severely inhibit the ability of utility providers to deliver services to the community – a hurricane may knock out the power grid or internet services. Such disruptions not only impact supply chains in the near-term, but inhibit recovery capabilities as well. The pandemic scenario is the second most disruptive – if employees are unable to arrive at work, supply chains suffer due to fluctuations in supply and demand. Additionally, a reduction in the size of the labor pool may lead to staffing shortages, further reducing organizational efficacy.

3.4.2 Modality Diversion Model

This model categorizes the diversion of goods between regions. As diversions are caused by projects that exist over decade-long life cycles, current system priorities will tend to evolve before new infrastructure can be built. The resilience of decisions across a set of scenarios is estimated with a resilience register. Analysis of enterprises such as a the Port of Virginia facility have been completed and sample results are discussed.

This model takes freight analysis framework (FAF) data from the United States Federal of Highway and Administration (FHWA) as input and outputs modality selection probabilities for each flow. For purposes of this work "flow" refers to a movement of all goods with a unique origin, destination, commodity type, and mode. Regional based analysis is sufficiently disaggregated to support transportation decision-making [27] and characterize large scale systems [28]. Exhibit 22 shows an example of the regions as pre-defined by FHWA for Virginia. The four regions Norfolk, Washington DC, Richmond, and Rest of Virginia, are each differently shaded. The FAF data is selected due to reliability and annual updating from the FHWA that is essential. The national scope is needed to compare regions of international freight movement. The developed model contributes a novel balancing of modelling complexity and aggregation of results enabling interpretation of results by a larger group of stakeholders which is key to support innovation [21, 29–31].

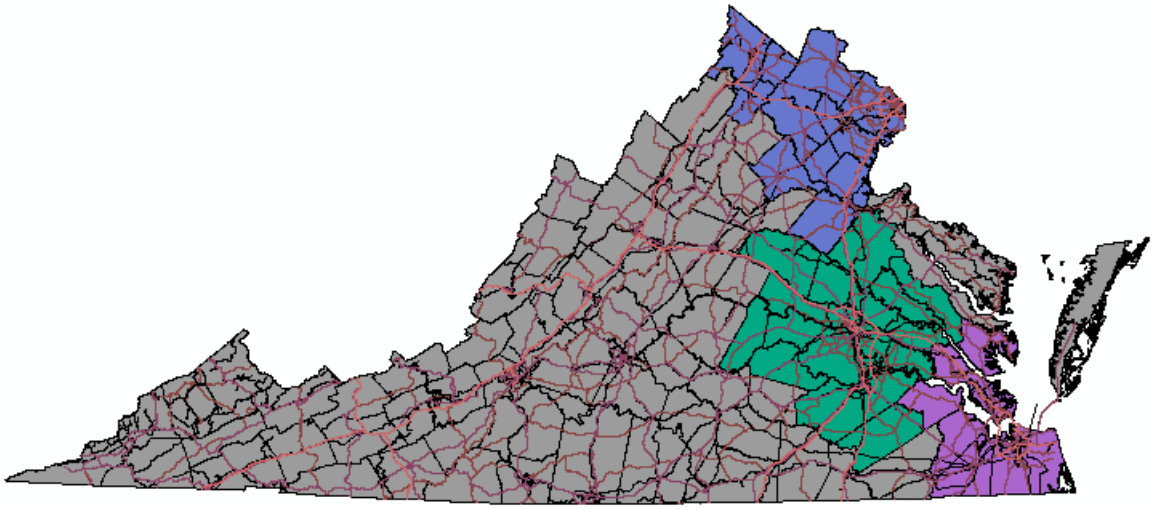


Exhibit 22: Map of Virginia FAF regions where “Rest of Virginia” is gray, and blue highlights the portion of the Washington DC Metro located inside Virginia

3.5 Case 4: Enterprise and Community Risk Model

Enterprise risk models are used to holistically manage risk and uncertainty, but are not developed enough to consider “organizational context” [32]. Those that consider stakeholder perspective, quality, or human factors [33–35] commensurate the perspectives rather than generating results unique to each stakeholder. The enterprise and community risk model advanced here is novel in providing these stakeholder unique results. The probabilities from the last modeling step are input to the risk model that filters on relevance and categorizes the types of risk. This second model identifies flows that will impact the priorities of stakeholders. The output from the diversion model is used to predict an ideal market where all goods flow. Exhibit 23 identifies categorization of modality diversion risk where inefficient indicates disagreement between predicted and actual flow and efficient indicates agreement estimated method.

	Inefficient Base Flow	Efficient Base Flow
Inefficient In Alternative Flow	Infrastructure Constraint	Alternative Region Loss Exposure
Efficient Alternative Flow	Base Region Loss Exposure	Market Parity

Exhibit 23: Categorization of modality diversion risk where inefficient indicates disagreement between predicted and actual flow and efficient indicates agreement

This is then contrasted with the actual flows to identify those at risk of modality diversion. The four categories will later be referred to as upper left quadrant, lower left quadrant, etc. Modality selections ideal for both the base region and the comparison region are labelled efficient and

those where the two sub models disagree are labelled inefficient. Performance metrics such as these are necessary to support policy [17]. Knowledge of the risk profile of projects is valuable to outside groups such as communities or enterprise which are lobbying for a project [16].

Exhibit 24 contains a boxplot showing there is significant capacity for modality shift of goods moving through Virginia. The method is general spatially and by commodity, unlike previously developed models that were limited to specific commodities and single transportation corridors.

Exhibit 24: Tons per year of goods flowing through Virginia with modality diversion opportunity

Results from this model are estimated diversion across the country for all commodities passing through a base case region. This enables the method to answer the following question for the second modeling step identifying changes in transportation flow that will be of greatest risk to stakeholders. Exhibit 25 shows the identification of latent demand in the logistics system for modality diversion of existing freight flows by commodity.

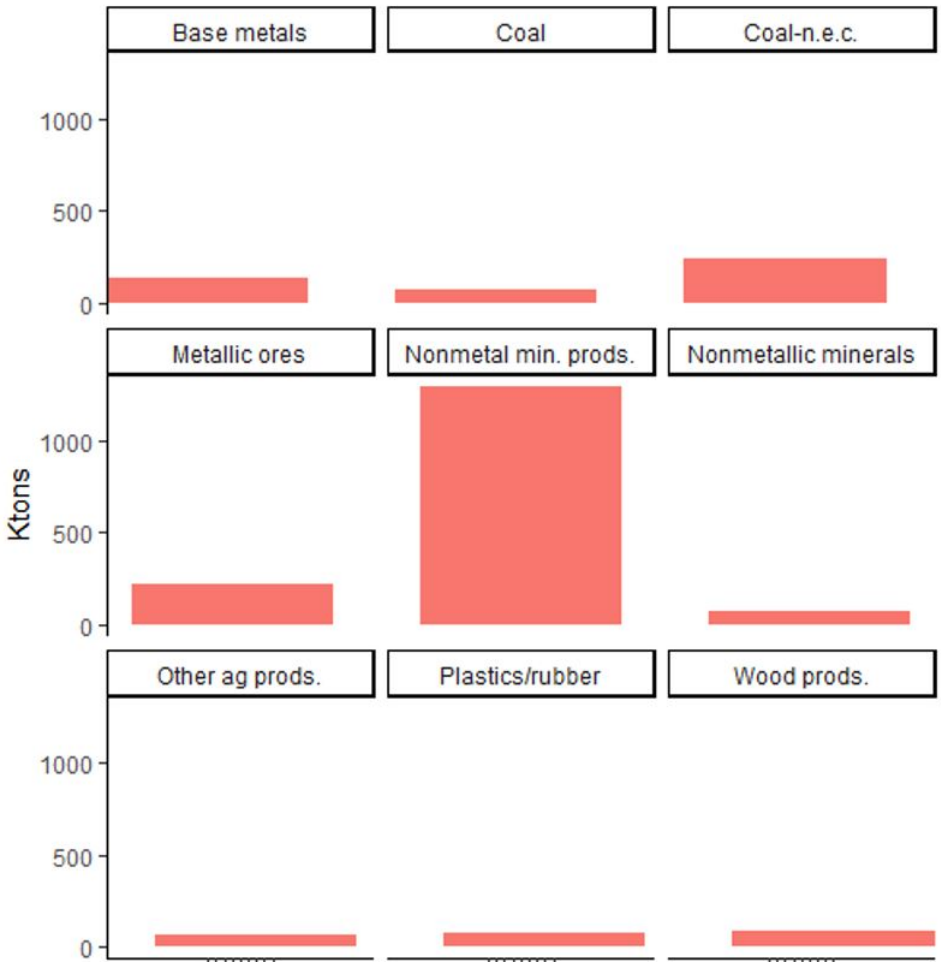


Exhibit 25: Tons per year of goods subject to modality diversion risk disaggregated by commodity types

Exhibit 26 shows a demonstration of results divided by region. As this model labels flows either freight or rail modality, two appropriate alternatives are logistic regression and random forest. The model has also been extended from this binary classification to a multiclass model such as multinomial. The regression models have similar residual error and as such the logistic regression model is selected for this work due to simple interpretability. However, for analysis where the factor interpretation is not relevant a random forest model can be used for the benefit of minimal improvement in residuals.

Exhibit 26: Tons per year of good flows subject to modality diversion broken down by destination regions

An example interpretation for each of the four quadrants is discussed for the Port of Virginia but the flexibility in this method is the ability to tailor interpretation to the specific stakeholder needs. First, the upper left quadrant represents flows that are not moving on the predicted modality for either the base or comparison region that implies there is a joint infrastructure constraint. Exhibit 27 shows an example visualization identifying regions at greatest risk by volume. For each flow in this quadrant investment in additional freight capacity is more likely to result in increased regional competitiveness. Each stakeholder may interpret this differently. For example, a port may lobby a transportation agency for infrastructure improvements, a warehouse might alter site selection based on expected resolution of the bottleneck, and community members may advocate directly to transportation agencies in the interest of bringing economic development to their region.

Exhibit 27: Regions of goods flow on unpredicted modality for both regions in a pairwise comparison where "Port" refers to the FAF region where the goods are flowing

Second, the upper right quadrant identifies flows that are moving efficiently through the base region but constrained in the alternative region. This can be interpreted as flows that are subject to gain for the base region and valuable to business, though as before each stakeholder would have different interpretations. Exhibit 28 contains an example of results in this quadrant where the nine regions with the greatest opportunity for the base region to increase competition are labeled. For example, the greatest value is in Philadelphia indicating a large amount of freight is currently moving there via an alternative region that could be moved more efficiently through the base region.

Exhibit 28: Regions with most tons of goods per year flowing on unpredicted modality representing regions of expansion opportunity for business or communities in the base case region

Third, the lower left represents flows that the base region may lose if competitive factors are not addressed. Exhibit 29 provides an example of results for the base region identifying the greatest area of potential loss is in Washington DC.

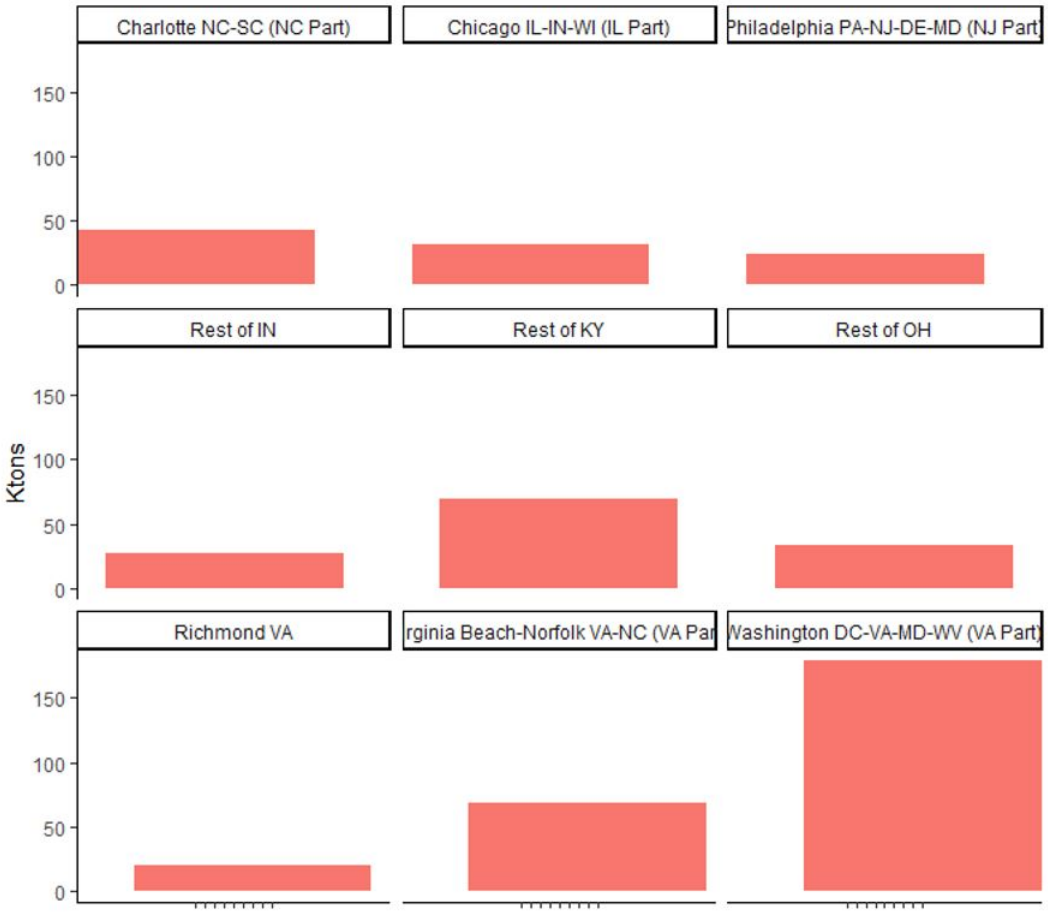


Exhibit 29: Tons of flow by destination that are moving more efficiently through an alternative region identifying demand that is subject to loss to another more competitive region

Finally, the lower right represents flows that are moving efficiently from both regions and are subject to cost or other service factors. Exhibit 30 contains an example of results that identify New York as the region where the base port could most increase demand through competitive pressures. Similarly, though of lower magnitude, the region with the most tons of competitive goods currently moving through the base region is Washington DC where the base region may lose business if the alternative port for example lowered costs.

Exhibit 30: Tons of flows that are competitive in both the base and alternative port in a pairwise comparison where those moving through the base region are blue and those moving through the alternative are red

3.6 Integration of the Results

The above section presented four cases covering important interests of the Crater region. The first case showed that natural disaster and pandemic scenarios are the most disruptive to Crater priorities.

The second case showed that a pandemic scenario is the most disruptive to regional employers, followed closely by natural disasters. Specifically schools and hospitals rise in importance during these scenarios.

The third case addressed logistics assets of the Crater region, and showed that a natural disaster scenario is the most disruptive to the system. Utility services and grocery distribution are particularly susceptible to these disruptions.

Finally, the above section presents an enterprise risk model utilizing modality diversion, which shows how the movement of goods change under disruptive scenarios.

4 Discussion and Recommendations

This report presented an implementation of the resilience register methodology for the Crater Planning District Commission. The focus of this report was on industry supply chain disruption and associated scenarios. Using a set of active projects managed through the CPDC, a set of the largest local employers, and a set of critical logistics assets, it was shown pandemics and natural disaster scenarios most disrupt the Crater region. Specifically, the Crater projects and local employers were affected more by the pandemic scenario than the natural disaster as they rely on the movement of the population. The logistics assets were affected more under a natural disaster scenario, as damage to infrastructure has a cascading impact on the entire logistics system. Of the seven scenarios tested, these two were least likely to be foreseen with the most sudden impacts. This supports the hypothesis that abrupt and difficult to predict scenarios are the most disruptive to the region. Further, the third-ranked scenario is a cyber security attack, another disruption that is difficult to foresee.

Modal diversion modeling identified the most at risk commodities and regions of either origin or destination that goods may leave the Crater region. This enables targeting of initiatives to the transportation corridors, modalities of freight, break-bulk, and others to the goods most likely to be shifted elsewhere or brought into the region. The Crater region can use information from these methodologies to inform decision making with regard to new projects, and prioritizing initiatives that are robust to these types of disruptions. Such as the natural disaster and pandemic scenarios which pose the greatest threat to Crater priorities. A set of major conclusions can be found in Exhibit 31. A set of resilience and mitigation actions can be found in Exhibit 32. A matrix outlining how case study conclusions relate to recommendations in Exhibit 33.

Index	Findings
f.01	Adaptations to Social Distancing
f.02	Disruption to Physical Infrastructure
f.03	Resilient Roadway Improvements
f.04	High Business Development Ranks
f.05	Dual Impact of Pandemics
f.06	Supply Chain Employer Resilience
f.07	Public School Resilience
f.08	High Ranking Utilities
f.09	Critical Roadways
f.10	Avoidance of Downtime
f.11	Disruptions to Military
f.i	Others

Exhibit 31: A set of conclusions based on the three case study assessments

4.1 Resilience to Natural Disaster Scenarios

As seen in Exhibit 21, resilience to natural disasters will largely focus on logistics assets. One method for reducing the impact of natural disasters and other stressors is r_1: *update development plans*, which includes a careful examination and updating of urban, natural resource, and land planning policies. For example, limiting urbanization in flood-prone areas would reduce the impact of storm events such as hurricanes [36]. Such actions can reduce the short and long-term impacts of natural disasters, enabling the region to avoid immediate disruptions and recover more quickly.

Index	Resilience/Mitigating Actions
r.01	Update Development Plans
r.02	Enhance Routes 460 and 58
r.03	Expand Rail Access
r.04	Rural Public Transportation
r.05	Site Development
r.06	Information Sharing
r.07	Employee Training Grants
r.08	On-the-Job Training Grants
r.09	Trucker Training
r.10	Service Industry Investment
r.i	Others

Exhibit 32: A set of recommendations to enhance the resilience of the Crater region and mitigate disruptive scenarios

Further, r_2: *enhancements to Route 460 and Route 58* will improve supply chain resilience of the

region [37]. Both routes are critical to the Port of Virginia and other logistics organizations. Ensuring that both roadways are easily accessible and reliable is crucial for the delivery of goods to local distribution centers, and from distribution centers to retail locations. Enhancements may include roadway expansion, improvements to road geometry, and improvements to road access. This is especially critical in a natural disaster scenario, in which roads may be unsafe or unavailable. Improving these assets can improve the speed of recovery efforts. Maintaining a high level of service even under disruption can reduce the costs of recovery [38].

Improving roads is one method for increasing resilience to disruption, but diversifying transportation methods also reduces the impact of natural disasters [37]. To that end, r_3: *expand rail access*, including the development of a rail hub in the Crater region to reduce dependence on roads for supply chain activities could be beneficial. If a natural disaster were to severely impact major roads in the region, rail may be a viable alternative for delivering goods and providing assistance for recovery. Additionally, railroads can be rapidly repaired by existing railroad rapid response repair teams trained to mitigating environmental damage to track. To accomplish this, Crater may pursue a grant through the Virginia Department of Rail and Public Transportation. The Rail Industrial Access Program specifically promotes rail development as a form of truck diversion [39]. By reducing dependence on roads, Crater can maintain greater supply chain capacity in the event of a natural disaster.

Another method for improving regional resilience to natural disasters is r_4: *rural public transportation*. Transit from rural areas to major urban hubs within the region as well as intercity service enables passengers to travel conveniently and increases the freedom of mobility for residents. In the event of a natural disaster, robust and reliable public transit can accelerate recovery efforts [40]. Further, investments in rural transportation offer opportunities to become thought leaders in infrastructure and green development. As an example, the Fresno Council of Governments – a regional agency similar to the Crater PDC – is developing a program to provide "inexpensive, zero emission, point-to-point rides for residents of rural Fresno..." [41]. The program is funded by a half-cent sales tax and a state grant, and provides on demand point-to-point service for residents who lack access to private vehicles using electric vehicles. Rural transit is helpful, but not accessible to all residents, especially low-income inhabitants of the region. A rural electric vehicle service provides two resilience benefits – improving the movement of residents and investing in green infrastructure. Inexpensive point-to-point transit allows residents to more easily reach employers and centers of commerce. Investing in a fleet of electric vehicles will enable the region to develop the green-infrastructure required to support electric vehicles, such as deploying charging stations.

Enhancing infrastructure via r_5: *site development* is one method for improving regional resilience to natural disasters. The Virginia Business Ready Sites Program (VBRSP) is a state organization that assists in infrastructure development [42]. The program has two focuses: 1) assessing the current readiness of a site and 2) develop a pool of potential sites. Sites are ranked in five tiers, with tier one sites having little to no infrastructure to tier five sites, which are considered "shovel ready" [43]. Developing a portfolio of high-tier sites enhances the business competitiveness and infrastructure of the region. The VBRSP provides grants to raise the tier level of existing sites, enabling the Crater region to invest in site enhancement more easily.

4.2 Resilience to Pandemic Scenarios

Contrasted with Exhibit 21, which shows the out-sized impact of natural disasters on infrastructure assets, Exhibits 12 and 15 show that a pandemic scenario has the greatest disruptiveness to Crater priorities. This is due, in part, to these analyses relating directly to employment. For the analysis of Crater projects outlined in Exhibit 9, initiatives such as business incubators and business development rate highly in the baseline and are severely disrupted by a pandemic scenario. Similarly, the analysis of major regional employers outlined in Exhibit 13 shows a greater disruption due to pandemics, especially with regard to schools. As such, increasing resilience to pandemics is critical for minimizing the impact of a disruptive event and accelerating recovery efforts.

During a pandemic it is critical to keep skilled staff employed, especially in supply chain positions. Warehouse and supply center employees, truckers, and retail workers are all critical for maintaining supply chain integrity. Workforce development is important for training and retaining a robust and highly-skilled workforce. One method for accomplishing this is by offering grants to employers to partially fund new certifications for employees, r_7: *employee training grants*. The Albemarle Commission, a regional council of governments in North Carolina, provides employers with up to $5,000 to train their employees. This includes training for new certifications such as forklift certifications and general skills training [44]. Prospective employees are also eligible for on-the-job training contracts, in which new employers can receive compensation for hiring and training a new employee for a high-skill position as in r_8: *on-the-job training grants* [44]. The Crater PDC could publish guidance for employers on searching for new employees efficiently and effectively, including where to post job openings, how to market a position, and how to train and retain a workforce. The Crater PDC is currently investing in business incubators and educational centers to stimulate local commerce, and these are excellent venues for deployment of these policies. Further, the Crater region already provides for both employers and employees through the Crater Regional Workforce Development Board, the Community College Workforce Alliance (CCWA), and the Virginia Career Works program. Continuing and expanding these programs may contribute to strengthening regional resilience [45].

Of particular interest to Crater stakeholders, including the Port of Virginia, is a focus on r_9: *trucker training*. In a pandemic scenario, the pool of available truck drivers is reduced, stressing the supply chain. By increasing the pool of available truck drivers, the region will be more resilient to a pandemic compared to a region with fewer available truck drivers. Investing in trucker training can increase supply chain resilience and enhance the advanced logistics systems of the region.

It has been shown that during a recovery from a pandemic, specifically the COVID-19 pandemic, hospitality, food service, and personal services are the slowest to recover [9]. It would benefit the region to invest in these industries to reduce the impact of of a pandemic, and aid in the recovery from a pandemic scenario as in r_{10}: *service industry investment*. This would include developing and recommending policies that allow these services to operate safely during a pandemic, such as promoting curbside service. Further, encouraging vaccinations for eligible populations when available, universal indoor masking, screening, and social distancing can protect vulnerable institutions and improve the resilience of the region [26].

To that end, it is crucial that the region synchronize preparedness and recovery efforts in a pandemic scenario through use of r_6: *information sharing*. That is, the Crater PDC region should de-

velop a plan that ensures all member jurisdictions are following the same set of expectations for a response to a scenario. This may include determining which businesses are eligible to remain open and at full capacity during the pandemic, how public services will operate in restricted conditions, and developing strategies to inform local communities about best practices. Many regulations may be enacted by the state or federal government, but even these regulations need to be effectively communicated to residents. Sharing data about a pandemic scenario is also important – a centralized resource allowing municipalities to share infection and vaccination rates will enable communities to make decisions that are best for the local population [36].

It should be noted that the Crater Planning District Commission is also involved in the development of the Richmond-Crater Hazard Mitigation Plan, which is a requirement of FEMA. This plan addresses the identification of hazards as well as risk assessments, and will be completed by June 30, 2022. Thus, this plan will be a major adjunct to this report.

			System 01. Crater Economic Development				System 02. Crater Largest Employers			System 03. Crater Supply Chain Assets			
			f.01 Adaptations to Social Distancing	f.02 Disruption to Physical Infrastructure	f.03 Resilient Roadway Improvements	f.04 High Business Development Ranks	f.05 Dual Impact of Pandemics	f.06 Supply Chain Employer Resilience	f.07 Public School Resilience	f.08 High Ranking Utilities	f.09 Critical Roadways	f.10 Avoidance of Downtime	f.11 Disruptions to Military
Resilience/Mitigating Actions	Other Stressors	r.01 Update Development Plans		✔				✔		✔		✔	✔
		r.02 Enhance Routes 460 and 58		✔	✔			✔		✔	✔	✔	
		r.03 Expand Rail Access		✔	✔			✔			✔	✔	
		r.04 Rural Public Transportation	✔			✔	✔		✔	✔	✔	✔	✔
		r.05 Site Development		✔						✔	✔		✔
	Pandemic Stressors	r.06 Information Sharing	✔				✔		✔	✔			✔
		r.07 Employee Training Grants				✔	✔	✔		✔		✔	
		r.08 On-the-Job Training Grants				✔	✔			✔		✔	
		r.09 Trucker Training	✔	✔	✔			✔			✔		
		r.10 Service Industry Investment	✔			✔	✔		✔			✔	

Exhibit 33: Matrix outlining which case study findings drive the opportunity for each recommendation

References

[1] Crater Planning District Commission, "Crater pdc boundaries," https://craterpdc.org/wp-content/uploads/2020/03/CraterPDC.pdf, accessed: September 2021.

[2] Crater PDC, "2021 comprehensive economic development strategy," Crater Planning District Commission, Petersburg, VA 23805, Tech. Rep., June 2021.

[3] M. L. Hassler, D. J. Andrews, B. C. Ezell, T. L. Polmateer, and J. H. Lambert, "Multi-perspective scenario-based preferences in enterprise risk analysis of public safety wireless broadband network," *Reliability Engineering & System Safety*, vol. 197, p. 106775, 2020.

[4] Virginia Code Commission, *Code of Virginia, Section 15.2-4207*, 2021.

[5] Crater Planning District Commission, "About us," https://craterpdc.org/about-us/, accessed: September 2021.

[6] U.S. Army, "U.s. army garrison fort lee," https://home.army.mil/lee/index.php, accessed: September 2021.

[7] U.S. Bureau of Labor Statistics, "Employment and wages, annual averages 2020," U.S. Bureau of Labor Statistics, Washington, DC 20212-0001, Tech. Rep., September 2021.

[8] Virginia Employment Commission, Economic Information Analytics Division, "Local area unemployment statistics (laus) - august 2021," Virginia Employment Commission, Richmond, VA 23230, Tech. Rep., September 2021.

[9] Chmura, "Economic impact of covid-19 on crater pdc and localities," Crater Planning Discrict Commission, Tech. Rep., January 2021.

[10] Y. Almoghathawi, K. Barker, C. M. Rocco, and C. D. Nicholson, "A multi-criteria decision analysis approach for importance identification and ranking of network components," *Reliability Engineering & System Safety*, vol. 158, pp. 142–151, 2017.

[11] Y. Y. Haimes, "Risk modeling, assessment, and management," 2015.

[12] H. Thorisson and J. H. Lambert, "On the "influence of scenarios to priorities" in risk and security programs," *Applied Risk Analysis for Guiding Homeland Security Policy*, pp. 1–24, 2021.

[13] Z. A. Collier, J. H. Lambert, and I. Linkov, "Analytics and decision-making to inform public policy in response to diverse threats," *Environment Systems and Decisions*, vol. 40, no. 4, pp. 463–464, 2020.

[14] ——, "Concurrent threats and disasters: modeling and managing risk and resilience," 2020.

[15] M. Alsultan, Z. A. Collier, and J. H. Lambert, "Risk-based priority setting for large-scale access management programs with uncertain mobility benefits and costs," *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, vol. 7, no. 1, p. 04020046, 2021.

[16] Z. A. Collier and J. H. Lambert, "Value of risk information in negotiations with evolving preferences," *Journal of Risk Research*, vol. 23, no. 10, pp. 1353–1369, 2020.

[17] K. Hollenback, J. H. Lambert, and I. Linkov, "Indicators and metrics of emerging country-level stem innovation," *IEEE Engineering Management Review*, vol. 48, no. 2, pp. 47–53, 2020.

[18] S. Carpitella, A. Certa, J. Izquierdo, and C. M. La Fata, "A combined multi-criteria approach to support fmeca analyses: A real-world case," *Reliability Engineering & System Safety*, vol. 169, pp. 394–402, 2018.

[19] D. J. Andrews, T. L. Polmateer, J. P. Wheeler, D. L. Slutzky, and J. H. Lambert, "Enterprise risk and resilience of electric-vehicle charging infrastructure and the future mobile power grid," *Current Sustainable/Renewable Energy Reports*, vol. 7, no. 1, pp. 9–15, 2020.

[20] C. W. Karvetski and J. H. Lambert, "Evaluating deep uncertainties in strategic priority-setting with an application to facility energy investments," *Systems Engineering*, vol. 15, no. 4, pp. 483–493, 2012.

[21] I. Linkov, B. D. Trump, J. M. Keisler, J. Cegan, C. M. Foran, Z. A. Collier, J. H. Lambert, and M. M. Kuklja, "Signals and metrics identifying partnerships for innovation," *IEEE Engineering Management Review*, vol. 48, no. 2, pp. 39–46, 2020.

[22] Y. Y. Haimes, S. Kaplan, and J. H. Lambert, "Risk filtering, ranking, and management framework using hierarchical holographic modeling," *Risk Analysis*, vol. 22, no. 2, pp. 383–397, 2002.

[23] P. Goodwin and G. Wright, "Enhancing strategy evaluation in scenario planning: a role for decision analysis," *Journal of management studies*, vol. 38, no. 1, pp. 1–16, 2001.

[24] A. Almutairi, Z. A. Collier, D. Hendrickson, J. M. Palma-Oliveira, T. L. Polmateer, and J. H. Lambert, "Stakeholder mapping and disruption scenarios with application to resilience of a container port," *Reliability Engineering & System Safety*, vol. 182, pp. 219–232, 2019.

[25] W. Turton and K. Mehrotra, "Hackers breached colonial pipeline using compromised password," https://www.bloomberg.com/news/articles/2021-06-04/hackers-breached-colonial-pipeline-using-compromised-password, June 2021, accessed: September 2021.

[26] National Center for Immunization and Respiratory Disease, "Guidance for covid-19 prevention in k-12 schools," Center for Disease Control and Prevention, Tech. Rep., August 2021.

[27] C. A. Pennetti, J. Jun, G. S. Jones, and J. H. Lambert, "Temporal disaggregation of performance measures to manage uncertainty in transportation logistics and scheduling," *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, vol. 7, no. 1, p. 04020047, 2021.

[28] Z. A. Collier, T. L. Polmateer, and J. H. Lambert, "Risk management decision making for security and trust in hardware supply chains," 2021.

[29] J. M. Keisler, Z. A. Collier, B. M. Ayyub, C. S. Dempwolf, J. M. Gibson, A. L. Porter, V. J. Schweizer, H. Thorisson, L. Wang, M. Ye *et al.*, "Modeling and analytics to support emerging international innovation partnerships," *IEEE Engineering Management Review*, vol. 48, no. 2, pp. 54–64, 2020.

[30] K. Klasa, B. D. Trump, I. Linkov, and J. H. Lambert, "Identifying new partnerships for innovation: Governance and policy challenges," *IEEE Engineering Management Review*, vol. 48, no. 2, pp. 26–38, 2020.

[31] F. Lian, J. Jin, and Z. Yang, "Optimal container ship size: a global cost minimization approach," *Maritime Policy & Management*, vol. 46, no. 7, pp. 802–817, 2019.

[32] K.-O. Davidsson and L. Falkman, "Scoping the field of enterprise risk management-and implementing it at kraftringen ab," 2021.

[33] S. Fan, J. Zhang, E. Blanco-Davis, Z. Yang, and X. Yan, "Maritime accident prevention strategy formulation from a human factor perspective using bayesian networks and topsis," *Ocean Engineering*, vol. 210, p. 107544, 2020.

[34] S. Sarıalioğlu, Ö. Uğurlu, M. Aydın, B. Vardar, and J. Wang, "A hybrid model for human-factor analysis of engine-room fires on ships: Hfacs-pv&ffta," *Ocean Engineering*, vol. 217, p. 107992, 2020.

[35] P. Trucco, E. Cagno, F. Ruggeri, and O. Grande, "A bayesian belief network modelling of organisational factors in risk analysis: A case study in maritime transportation," *Reliability Engineering & System Safety*, vol. 93, no. 6, pp. 845–856, 2008.

[36] M. Bonato, B. Sambo, A. Sperotto, J. H. Lambert, I. Linkov, A. Critto, S. Torresan, and A. Marcomini, "Prioritization of resilience initiatives for climate-related disasters in the metropolitan city of venice," *Risk Analysis*, 2021.

[37] D. Hendrickson and R. Green, "Personal communication to pis," Personal Communication, Norfolk, VA, October 2021.

[38] C. A. Pennetti, D. J. Andrews, T. L. Polmateer, and J. H. Lambert, “Geospatially distributed safety and performance benefits for projects of a transportation system,” in *2020 IEEE International Systems Conference (SysCon)*, 2020, pp. 1–7.

[39] Virginia Department of Rail and Public Transportation, “Drpt grants: Rail industrial access,” Richmond, VA, 2021.

[40] Fresno County Rural Transit Agency, “Public transit planning,” https://www.fresnocog.org/project/public-transit-planning/, Fresno, CA, November 2021.

[41] M. Curry, “Fresno county launches rural electric microtransit pilot,” https://cal.streetsblog.org/2020/10/23/fresno-county-launches-rural-electric-microtransit-pilot/, October 2020.

[42] D. L. Alderson, G. G. Brown, and W. M. Carlyle, “Operational models of infrastructure resilience,” *Risk Analysis*, vol. 35, no. 4, pp. 562–586, 2015.

[43] Virginia Economic Development Partnership, “Virginia business ready sites program (vbrsp),” https://www.vedp.org/vbrsp, Richmond, VA, January 2021.

[44] Northeast Workforce Development Board, “Grants and services,” https://nwdbworks.com/business/grants-services/, 2021.

[45] Crater Regional Workforce Development Board, “Virginia career works: Crater region,” https://vcwcraterregion.com/, 2021.