Managing Operational and Environmental Risks in the

Strategic Plan of a Maritime Container Port

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***Abstract*—Shipping trends in technology, regulation, energy and environment require maritime container ports to adapt their operations to better suit current and future conditions. This paper focuses on innovative solutions in three main areas of interest for ports: (1) clean energy technologies, (2) alternative financing and (3) automated process technologies. In this analysis, these areas of interest are explored using the Port of Virginia as a case study. Results are derived using scenario analysis methodology drawn from systems, risk and resilience analysis. Investment strategies in renewable energy sources are evaluated and project funding approaches, including the use of green bonds, are explored. AI systems relevant to port operations integration and container security are also described. The key results of this paper are twofold: (1) a demonstration ranking of initiatives for a port strategic plan and (2) a ranking of scenarios by their disruption on initiative impact. The results of the case study are of interest to the strategic planners at industrial ports and the maritime industry.**

Keywords— Systems engineering, risk analysis, logistic systems, hybrid threats, optimization, sustainability, emergent conditions, strategic plans

I. Introduction

Maritime shipping ports are critical hubs in supply chains, acting as a key node for intermodal transport between ships, trucks, and rail. They directly support global and regional economic activity, transportation network systems, and job growth [1]. As the world's economy becomes more globalized, it is essential for ports to develop the capacity to adapt to emergent conditions and disruptive scenarios [2]. For purposes of this work, we define resilience as "the ability of the system to bounce back after a shock and return to its normal value delivery levels" [3]. Investments to maintain or increase resilience against man-made or natural disruptions are vital to the health of the global supply chain and therefore economic activity. This paper demonstrates a scenario-based preference model that can be used to assess the resilience of maritime shipping ports using criteria, initiatives, and emergent conditions to define the most disruptive scenarios. It then makes recommendations based on current technology to help port preparedness against emergent conditions and increase resilience of the port business model [4].

The model was developed in the context of a port amid the beginning of the COVID-19 pandemic, and this demonstration was done as global shipping began to return to pre-pandemic levels. The focus is on modernizing the port through new technology, data, and sustainability innovations. The demonstrations show a prioritization of initiatives aimed at increasing the resilience of the port to emergent conditions. Highly disruptive initiatives were selected for further analysis and a case study performed at the Port of Virginia (POV) to recommend strategic investments in support of the port's sustainability and digital infrastructure efforts. The selected initiatives are: (1) clean energy technologies, (2) alternative financing and (3) automated process technologies.

As climate change urgency has altered the cost of carbon emissions, environmental sustainability has become a vital criterion in measuring port performance [5]. Current technologies render ports an ideal location for renewable energy projects such as wind energy. A thriving industrial port is vital to operating offshore energy systems [6]. Centering offshore wind terminals at a port simplifies supply chains and dramatically reduces implementation, transportation and maintenance costs [6].

Unlike wind energy, hydrogen energy is a storable energy source that can be used to power cars, generators and other systems not linked in the electric grid. A hydrogen fuel cell uses the chemical energy of hydrogen to cleanly and efficiently produce electricity [7]. Fuel cells can be used in a wide range of applications, including but not limited to transportation, material handling, and stationary/portable backup power applications [7]. Fuel cell power boasts higher efficiency and lower emissions than diesel powered port equipment, including Rubber Tired Gantry (RTG) cranes, forklifts, straddle carriers, reach stackers and shuttle trucks, currently in use at most ports [8]. Hydrogen fuel cells can be refueled with a hose or nozzle very quickly, similar to diesel refueling [8]. Furthermore, port applications that run on hydrogen fuel cell/onboard hydrogen storage hybrid systems are much lighter than those that run on lithium-ion batteries, thus enabling larger driving distances [7]. Clean hydrogen production requires a renewable energy source, such as a wind turbine, which provides power to an electrolysis facility where water and energy is used to create hydrogen using electrolysis [9]. Thus, the integration of alternative energy systems is vital for maximizing return on investment and achieving the economies of scale necessary to reap economic and environmental benefits.

Developments in the offshore mariculture sector have also yielded possibilities to reduce carbon emissions via sustainable fish farms. Livestock currently account for 9.9% of US greenhouse gas emissions [10]. Offshore mariculture has the potential to decrease consumer reliance on livestock to subsequently reduce carbon emissions in the food sector. Furthermore, offshore mariculture platforms can be integrated with renewable energy systems, such as wind and hydrogen, to amplify sustainable benefits [11].

To fund such projects, alternative financing methods play a crucial role. The emergence of the green bond market provides an innovative tool for ports to engage in sustainable initiatives [12]. A green bond is a financial debt security tool whose use of proceeds must be committed towards green initiatives [12]. Aside from this caveat, they are similar in price and returns as normal bonds. When the issuer of a bond labels it as green, it must go through a third-party certification process to ensure that it falls in line with the Green Bond Principles (GBP) as outlined by the International Capital Market Association (ICMA) [13]. Once this process is completed and the bond is issued, entities can begin investing with the reassurance that their funds will be put towards green projects. They provide a number of benefits for issuers, such as enabling projects at lower costs of capital, strengthening brand value, and increasing demand among investors [15].

Automation will also play a key role in future port operations. Efficiency has long been a priority for ports to keep up with demand due to increased volume [16]. Automated technologies increase efficiency via optimizing processes, such as ship and truck scheduling and container stacking [16].

Establishment of a digital ecosystem at a port would allow the port to provide extensive digital services, bringing in a new revenue stream through data services and adding a new dimension to the port's business plan. The Port of Rotterdam has plans to implement a digital ecosystem, the Port Community System (PCS) [16]. A main challenge preventing full implementation of the PCS is the lack of international standards for data sharing. Standards for data ownership, usage, and sharing must be clear and security of information must be ensured through cyber-security investment [16]. Customers increasingly demand value-added information services to get a better insight into related processes, especially intermodal transport [16]. Improved gathering, storing, processing, and analysis of various and large data sources requires accurate data collection, potentially through the Internet of Things (IoT), sophisticated techniques such as machine learning, and trust between stakeholders [17].

Recent advances in asset tracking security technologies also have the potential for implementation in the near future. These technologies could contribute to filling the cyber security infrastructure gap in the port industry while also contributing to port efficiency and data management [18][30]. Radio frequency tags in conjunction with centralized databases and human interfaces are at the forefront of asset tracking technologies. Through these technologies, a port can take advantage of its collection of data producing assets and begin to build a larger database for tracking port activities and efficiency [18][30]. The importance of asset tracking technology and centralized databases to the port is reinforced by their capability to provide valuable data for efficiency analysis, facilitate appropriate physical and data related security measures, and the modularity of asset tags which supports gradual implementation and maintenance. Implementing an asset management system and centralized database reduces total costs for the port and increases annual container throughput by minimizing down-time for port infrastructure [19].

II. Methods

This section describes a scenario-based methodology for prioritizing initiatives and determining the most disruptive scenarios on system performance. This approach follows that of Hassler, et al (2018) [4]. Success criteria, based on stakeholder objectives, are determined to evaluate system performance. The set $C = \{c_1, ..., c_k\}$ represents the robust set of criteria identified through stakeholder interviews and reviews of relevant literature. Each criterion is assigned a baseline relevance based on discussions with stakeholders. Initiatives are a set of actionable alternatives, such as policy alterations and investment in technology. The set $X = \{x_1, ..., x_k\}$ represents the set initiatives developed from stakeholder and competitor expertise, as well as literature reviews. Initiatives are evaluated by assessing their impact on each criterion. Neither of these sets should be considered exhaustive and could be altered with additional input form stakeholders.

Emergent conditions represent plausible future events and trends that could impact the effectiveness of initiatives. These conditions have the potential to change the baseline relevance of criteria, disrupting the ranking of initiatives. The set $E = \{e_1, ..., e_j\}$ represents emergent conditions developed from reviews of relevant third-party literature. Scenarios, the set $S = \{s_1, ..., s_k\}$, are synthesized from the emergent conditions and represent events with a high magnitude of impact on system performance.

After determining the relevant model features, an assessment of each criterion's baseline relevance to each stakeholder is performed. Drawn from interviews with stakeholders, each criterion j is designated as holding 'high', 'medium' or 'low' relevance for each stakeholder p. These categories are mapped to weights agreed upon by experts. For each stakeholder perspective, the $m_B \times n$ baseline matrix w_B^p is filled by entries of the normalized relevance assessments w_{jB}^p . After determining the baseline matrices for each stakeholder, the change in respective criterion relevance was evaluated for each scenario. Using stakeholder input and relevant literature, scenario impacts were categorized as either "decreases", "decreases somewhat", "no effect", "increases somewhat" and "increases". These measures are mapped to weights, w_{jk}^p , which form the entries of the set of $m_k \times n$ impact matrices w_k^p.

After determining the impact of scenarios on criteria weights, the impact of each initiative on respective criterion is evaluated, drawn from interviews with stakeholders and literature research. To qualitatively measure these relationships, the categories: 'strongly agree', 'agree', 'somewhat agree' and 'disagree' that an initiative impacts a criterion, were used. Each category maps to a weight determined by stakeholder opinions and previous models. The impact matrix X is created with entries x_{ij} representing the assigned weight of the impact of alternative a_i on criterion c_j. Each initiative is then assigned a score according to the linear additive value function in Equation 1.

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

Initiatives may then be ranked, with a higher value score indicating a higher priority initiative. $R(x_i)_k^p$ represents the ranking of initiative x_i under scenario s_k for stakeholder perspective p. The disruptiveness measure $D(s_k)^p$ for a given scenario k for each stakeholder is the sum of square rankings given in Equation 2.

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

This analysis achieves two objectives: (1) initiatives are ranked according to priority, and (2) scenarios are ranked according to their disruption of the initiative rankings.

III. Demonstration

The demonstration section applies the methodology outlined in Section II on the operational and environmental risks to industrial ports. A set of performance criteria are listed in Table I. These performance criteria were identified via interviews with port executives and analysis of a port master plan [20]. Baseline criteria relevance was then established using input from the port and is also included in Table I. A set of initiatives, displayed in Table II, were drawn from a port master plan and background research into developing port technology. Emergent conditions were developed from port interviews and analysis of research. The emergent conditions were grouped to form scenarios. These scenarios include Funding Decrease (s.01), Natural Disaster (s.02), Pandemic (s.03), Increased Environmental Regulation (s.04), Green Bonds Become Widespread (s.05), Green Technology Movement (s.06), Population Changes (s.07), and Cyber Security Attack (s.08).

TABLE I. Criteria of Scenario Analysis

Index	Criteria
c.01	Ease of Logistics
c.02	Efficiency
c.03	Throughput Volume
c.04	Safety & Security
c.05	Carbon Footprint
c.06	Innovation
c.07	Low Operational Cost
c.08	Compliance with Regulation
c.09	Power Grid Resilience
c.10	Global Port Standing
c.11	Keeping up with Demand
c.12	Global Connectivity

TABLE II. Initiatives of Scenario Analysis

Index	Initiative
x.01	Fuel Cell Implementation
x.02	Cold Ironing Infrastructure
x.03	Dispatching Automation with Data Integration
x.04	Port Integration
x.05	Emissions Control Capacity over Port Pollutants
x.06	Automated Processing of Documents
x.07	Dispatching Augmented Operations
x.08	Augmentation of Offshore Wind Projects
x.09	Staging of Superport
x.10	Development of Offshore Blue Hydrogen Station
x.11	Development of Offshore Mariculture-Energy Platform
x.12	Hydrogen Powered Trucks
x.13	CO2 Capture & Storage under the Chesapeake
x.14	Hydrogen Pipeline Infrastructure
x.15	Flooding Resilience Measures
x.16	Issuance of Green Bonds for Funding
x.17	Increased Cyber Security Infrastructure
x.18	Increased Cyber Security Insurance
x.19	Implementation of MAST Technology
x.20	Port Interface for Tracking Assets
x.21	Post-Panamax Cranes
x.22	Additional stacks

Technology Movement (s.06), Population Changes (s.07), and Cyber Security Attack (s.08)

Using input from port executives and analysis of current research, the impact of initiatives on each criterion was categorically assessed as: 'strongly impacts', 'impacts', 'somewhat impacts' and 'does not impact'. The impact of scenarios on criteria relevance was also qualitatively assessed using the categories: "decreases", "decreases somewhat", "no change", "increases somewhat" and "increases". The qualitative assessments of initiatives and scenarios were then mapped to weights decided upon by stakeholders and experts. This methodology resulted in a ranking of initiatives and disruption scores for scenarios.

IV. Analysis of Selected Initiatives

A. *Clean Energy technologies*

The emergence of new technologies and large-scale investment in clean energy initiatives has led to many promising avenues for replacing fossil fuels with renewable energy sources. Offshore wind power, represented by initiative $x.08$: *'Augmentation of Offshore Wind Projects'*, has already proven its effectiveness as a reliable and scalable energy alternative. For example, an offshore wind terminal operated by the Port of Rotterdam accounts for 10% of all Dutch energy production and expects that to rise to 40% by 2050 [6]. In the United States, offshore projects launched off the coasts of New Jersey, Massachusetts and Virginia are expected to be operational by 2030 [21]. Technology harnessing wave power has also emerged as a source of energy for offshore platforms [22].

In addition, hydrogen energy serves as a promising renewable energy alternative. Recent investments in hydrogen energy include construction of electrolysis facilities at the Port of Rotterdam (represented by initiative x_{10} : *'Development of Offshore Blue Hydrogen Station'*) and laying of hydrogen pipelines (represented by initiative x_{14}: *'Hydrogen Pipeline Infrastructure'*) to the Rhineland-Westphalia region [23]. Recent initiatives regarding the uptake of hydrogen fuel cells (x.01: *'Fuel Cell Implementation')* in port environments have also shown promising results. Currently, fuel cells have been marketed for electric power generation in three different ways: for generation of portable electrical energy, for generation of stationary electric power, and for use in vehicles [24]. There are many current missions being undertaken by companies such as Orsted and BP to create renewable green hydrogen, utilizing sources such as wind turbines to power an electrolysis facility. Ports should look to partner with these energy companies and implement a fleet of fuel cell-powered land vehicles.

Deployment of a small fleet of hydrogen fuel cell-powered vessels could justify a cost-effective hydrogen production facility (electrolysis facility) in the future [25]. Initially, the electrolyzer only needs to provide enough hydrogen to power port-specific hydrogen fuel cell-powered equipment, but there should be plans to expand its capacity to support future hydrogen projects. Once an electrolysis facility is operational and in close proximity to the port, this will enable fully emissions-free cold ironing, where ocean going vessels can connect to shore-side electricity powered by hydrogen and reduce their idling emissions to zero (x.02: *'Cold Ironing Infrastructure'*) [25].

Research into deep sea mariculture systems has also determined that a 'blue and green' solution is required to make offshore fish farming economically viable [11]. Among the most promising designs is the result of the EU funded project H2Ocean, which integrates mariculture infrastructure with an energy system that harnesses wind and wave power to produce storable hydrogen energy [11]. This integrated system is represented by the alternative x_{11}: *'Development of Offshore Mariculture-Energy Platform'*.

B. *Alternative Financing*

The emerging green bond market, represented by x.16: *'Issuance of Green Bonds for Funding'*, provides a possible avenue for ports to finance a number of environmentally friendly initiatives over the course of the next several decades. The Port of Los Angeles' series of $35 million in green bonds issued in 2016 illustrate the feasibility of this alternative financing method for future sustainability projects at industrial ports [26]. The Port of LA has highlighted several categories for use of proceeds, including renewable energy, green buildings, green transportation, pollution prevention and control, and terrestrial and aquatic biodiversity conservation [26]. The emergence and rapid rise in issuance of green bonds since their inception in 2009 signals a global interest in the sustainability market with widespread benefits [27]. These benefits include: a favorable sustainability reputation among clients and the public, as the issuer is signaling a commitment to values the investors find important; access to a larger and more diverse investor base, since green bonds are being sought out by a growing class of investors; and increased demand, as green bonds tend to have higher rates and wider margins of oversubscription than normal bonds [28]. Looking at the initiatives listed in Table II, there are a number of areas where seaports can get involved with green bonds, such as x.01 (fuel cell implementation) and the various sustainable integration projects listed in x.08 through x.13.

C. *Automated Process Technology*

Rotterdam, a global leader in port digitalization, laid out a future vision for their own suite, named Digital Business Solutions [16]. The vision includes four levels: (1) implementing a port management system that supports administrative and financial processes of port calls and facilitates the digitization and data collection of the port, (2) implementation of a Port Community System (PCS), which provides a neutral base for digital exchange of information within the port community, requiring cooperation across stakeholders, (3) implementation of this PCS to guide cargo over all transport modes and transshipment hubs, and select the most efficient route of transport, and (4) expanding communications to other ports to allow all community members to respond in real time to changes in schedules at other nodes in the supply chain [16]. These levels are represented by x.03: *'Dispatching Automation with Data Integration'*, x.04: *'Port Integration'* and x.07: *'Dispatching Augmented Operations'*.

An example of a port in the beginning stages of the PCS process is The Port of Virginia, who has already implemented new technology such as the PRO-PASS truck reservation system [29]. The port is looking for partners in the technology sector including IBM as a data broker, and is planning a new yard planning tool utilizing AI and machine learning [29]. POV is already seeing benefits from these efforts, as PRO-PASS is significantly decreasing missed reservations, truck visits with turn time over 2 hours, and time for truck moves across all terminals [29]. Ports should continue moving forward to a goal of monetizing a Port Community System similar to what is described here and becoming not only a port but also an information services company.

In addition, automated asset tracking systems provide ports the potential for more efficient and safer operations. Currently, many ports across the US are seeking or have implemented asset tracking systems [30][18]. Some of these systems, such as the currently developing asset tracking system at the Port of Longview, have focused on geographic information system centered computerized maintenance management [30]. A major benefit of asset tracking, represented by x.20 *'Port Interface for Tracking Assets'*, is the integration of autonomous maintenance systems. By collecting data volumes on port assets, the port can make better educated decisions about when to replace equipment and whether the maintenance schedules for individual pieces of equipment should be reactive or predictive [19]. Improved scheduling can decrease down-time for maintenance while also decreasing overall cost to the port.

Panama Ports Company demonstrated this by reducing maintenance costs by 50% through implementing predictive maintenance [19]. Bringing asset data into a centralized database can also have applications in pollution management and reduction for the port. A centralized database can be the driver for a human interface used to visualize port activity in real time and get a rendering of every port asset at any given time [31].

V. RESULTS

Fig. 1 is a visualization of POV's ranking of initiatives. The black bars indicate a respective initiative's baseline ranking. Initiative's highest and lowest ranking in a given scenario is also shown. The blue bar indicates an increase in the initiative's priority given a specific scenario, while the red bar indicates a decrease. The range of these bars determine initiative resilience. x.08: '*Augmentation of Offshore Wind Projects'* is the highest ranking and most resilient initiative; offshore wind investment has the highest baseline priority and 'low ranking'. x.04: '*Port Integration'* and x.07: '*Dispatching Augmented Operations'* also have a high baseline priority and rank first in at least one scenario. The ranges of x.01: '*Fuel Cell Implementation'* and x.21: '*Post-Panamax Cranes'* indicate that these initiatives are resilient to scenario disruption.

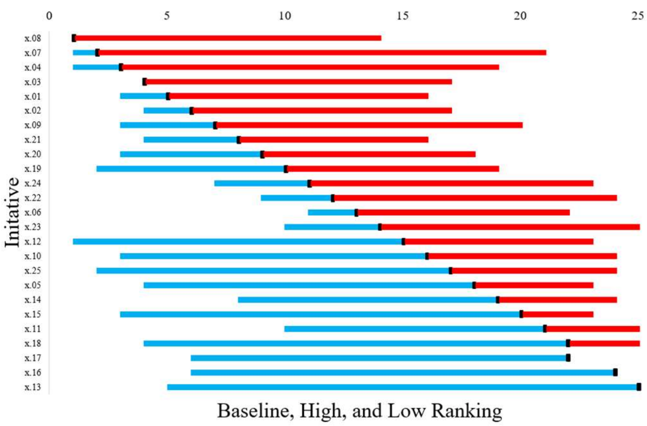

Fig. 1. Prioritization of initiatives for the container port showing the baseline, high, and low ranks and normalized disruptive scores for each scenario

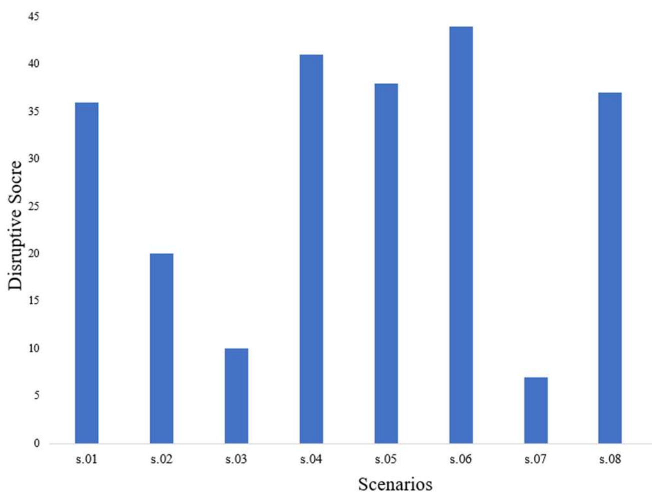

Fig. 2. Normalized disruptive scores for each scenario for the container port

Fig. 2 shows each scenario's normalized disruption score out of a maximum of 100. The most disruptive scenario to the ranking of initiatives is s.06: '*Green Technology Movement*'. Two other scenarios, s.04: '*Increased Environmental Regulation*' and s.05: '*Green Bonds Become Widespread*', have a similar magnitude of disruption on the emergent conditions. The least disruptive scenario is s.07: '*Population Shifts*'.

VI. Conclusion

Key results for enterprise risk analysis are summarized in Table III. It is clear that the climate change response will play a crucial role in determining success of port initiatives in the future. Each of the top three most disruptive scenarios involve future conditions that could emerge as industries and governments respond to the increasing urgency of climate change. Ports would be best served to monitor changes in the green technology industry, the green financing market and environmental policy in their investment prioritization process.

Investment priorities for ports should include investment in some combination of automated technologies and renewable energy infrastructure. Augmenting offshore wind capabilities is the highest ranking and most resilient initiative in the analysis, indicating that it should be a main priority for ports where this infrastructure is feasible. Hydrogen fuel cells, clusterport staging and cold ironing infrastructure are other renewable energy initiatives that should be prioritized by ports. Multiple automated technology initiatives rank first in some scenarios. Of the ten highest ranking initiatives, five are related to automating port functions. Ports should prioritize automated technologies for integrating port data and tracking assets.

TABLE III. Key Results for Enterprise Risk Analysis

Type of Result	Description
Most Disruptive Scenarios	The environment will play a crucial role in future port initiatives, as s.06: Green Technology Movement, s.04: Increased Environmental Regulation and s.05: Green Bonds Become Widespread are the most disruptive scenarios.
Least Disruptive Scenarios	s.07: Population Shifts is the least disruptive on the ranking of port initiatives.
Highest Ranking Initiatives	x.08: Augmentation of Offshore Wind is the highest-ranking initiative, while x.07: Dispatching Augmented Operations and x.04: Port Integration also have a high baseline priority and rank first in some scenarios.
Most Resilient Initiatives	x.08: Augmentation of Offshore Wind maintains the highest baseline ranking as well as the highest 'low ranking'. The rankings of x.01: Fuel Cell Implementation and x.21: Post-Panamax Cranes at VIG are fairly consistent across scenarios and are generally within the top half of initiatives.

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