Chapter 7
Seaport Climate Vulnerability Assessment at the Multi-port Scale: A Review of Approaches

R. Duncan McIntosh and Austin Becker

Abstract In the face of climate change impacts projected over the coming century, seaport decision makers have the responsibility to manage risks for a diverse array of stakeholders and enhance seaport resilience against climate and weather impacts. At the single port scale, decision makers such as port managers may consider the uninterrupted functioning of their port the number one priority. But, at the multi-port (regional or national) scale, policy-makers will need to prioritize competing port climate-adaptation needs in order to maximize the efficiency of limited physical and financial resources and maximize the resilience of the marine transportation system as a whole. This chapter provides an overview of a variety of approaches that set out to quantify various aspects of seaport vulnerability. It begins with discussion of the importance of a "multi-port" approach to complement the single case study approach more commonly applied to port assessments. It then addresses the components of climate vulnerability assessments and provides examples of a variety of approaches. Finally, it concludes with recommendations for next steps.

Keywords Seaport • Port • Shipping • Climate assessment • CIAV • CCVA • Resilience • Climate change vulnerability assessment • Comparative assessment • Multi-port assessment • Indicator-based assessment • Regional scale assessment

7.1 Seaports Are Critical, Constrained, and Exposed

Seaports represent an example of spatially defined, large scale, coast-dependent infrastructure with high exposure to projected impacts of global climate change (Becker et al. 2013, Hanson et al. 2010, Melillo et al. 2014). Seaports play a critical role in the global economy, as more than 90% of global trade is carried by sea (IMO

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2012). A disruption to port activities can interrupt supply chains, which can have far reaching consequences (Becker et al. 2011b, 2013, IPCC 2014a). Seaports are inextricably linked with land based sectors of transport and trade, and serve both the public and private good. Globally, climate change adaptation is still in the planning stages for most seaports (Becker et al. 2011a), yet the inevitable imperative for climate resiliency looms, as atmospheric concentrations of greenhouse gasses, the primary driver of climate change (IPCC 2013), continue to accumulate (WMO 2015). Indeed, most aspects of climate change will persist for centuries even if anthropogenic emissions of carbon dioxide were halted today (IPCC 2013).

Functionally restricted to the water's edge, seaports will face impacts driven by changes in water-related parameters like mean sea level, wave height, salinity and acidity, tidal regime, and sedimentation rates, yet they can also be affected directly by changes in temperature, precipitation, wind, and storm frequency and intensity (Koppe et al. 2012). The third U.S. National Climate Assessment (NCA) (Melillo et al. 2014) of the U.S. Global Change Research Program notes that impacts from sea level rise (SLR), storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, and other climatic conditions are already affecting the reliability and capacity of the U.S. transportation system. While the U.S. NCA predicts that climate change impacts will increase the total costs to the nation's transportation systems, the report also finds that adaptive actions can reduce these impacts.

In the face of these challenges, port decision makers have the responsibility to manage risks for a diverse array of stakeholders and enhance seaport resilience against climate and weather impacts. At the single port scale, decision makers such as port managers may consider the uninterrupted functioning of their port the number one priority. But, at the multi-port (regional or national) scale, policy-makers will need to prioritize competing port climate-adaptation needs in order to maximize the efficiency of limited physical and financial resources and maximize the resilience of the marine transportation system as a whole.

Recognizing a regional or national set of ports and waterways as part of an interconnected marine transportation system (MTS),[1] how should responsible decision makers prioritize the climate adaptation decisions for systems that involve multiple ports? This chapter provides an overview of a variety of approaches that set out to quantify various aspects of seaport vulnerability. It begins with discussion of the importance of a "multi-port" approach to complement the single case study approach more commonly applied to port assessments. It then addresses the components of climate vulnerability assessments and provides examples of a variety of approaches. Finally, it concludes with recommendations for next steps.

[1] The marine transportation system, or MTS, consists of waterways, ports, and inter-modal landside connections that allow the various modes of transportation to move people and goods to, from, and on the water. (MARAD 2016)

7.2 Impediments to Multi-port Adaptation

A 2016 study which quantified the resources, time and cost of engineering minimum-criteria "hard" protections against sea level rise for 223 of the world's most economically important seaports, suggested insufficient global capacity for constructing the proposed protective structures within 50–60 years (Becker et al. 2016). As individual actors and governments consider climate-adaptation solutions for seaports, a global uncoordinated response involving heavy civil infrastructure construction may be unsustainable simply from a resource availability perspective (Becker et al. 2011b, 2016, Peduzzi 2014). Given limited financial and construction resources for the implementation of engineered protection across many ports, some form of prioritization for national and regional-scale climate-adaptation will likely be necessary. Port authorities have expressed that although general concern for climate change exists, awareness of sea level rise is limited and the planning for adaptation is lacking (Becker et al. 2010).

The implementation of strategic adaptation on a multi-port scale is further challenged by complex and dynamic regional differences defined by varying landscapes and geographies that are far from uniform in their climate change vulnerability. Some ports, for example, may by surrounded by lowlands at risk to inundation from sea level rise. For these ports, the ground transportation systems may by more threatened than the port itself (e.g., Port of Gulfport, MS). In other areas, storm surge might be amplified by the geomorphology of an estuarine system (e.g., Providence, RI).

At the single port scale, the design of engineering protection during a port's expansion can benefit by estimating how long the infrastructure will last and withstand future impacts (Becker et al. 2015). However, justifying major investments is challenged by the uncertainty involved in projecting the extent to which ports will be impacted this century (Becker and Caldwell 2015). In the following section, we first discuss the concept of measuring vulnerability, risk, and resilience, then describe assessment methods employed by individual ports. Following, we discuss the need for multi-port assessment approaches and work in this area to date.

7.3 Assessing Climate Vulnerabilities to Facilitate Far-Sighted Resilience Planning

Vulnerability and resilience are two theoretical concepts, sometimes defined complementarily, other times described as opposite sides of the same coin, (Gallopín 2006, Linkov et al. 2014) that have gained increasing attention in the climate change adaptation and hazard risk reduction literature. As theoretical notions, resilience and vulnerability are not directly measurable, and some researchers (Barnett et al. 2008, Eriksen and Kelly 2007, Hinkel 2011, Klein 2009, Gudmundsson 2003) have criticized attempts to assess them as unscientific and or biased. However, policymakers are increasingly calling for the development of methods measure relative risk, vulnerability, and resilience (Cutter et al. 2010, Hinkel 2011, Rosati 2015).

The International Association of Ports and Harbors (IAPH) defines seaport vulnerability using three components: *exposure*, *sensitivity*, and *adaptation capacity* (Koppe et al. 2012). Measuring a port's *exposure* requires downscaled regional climate projections which may not yet be available for some port regions, and where they are available, necessarily contain uncertainty. A port on the west coast of the U.S., for example, may be considered less exposed to hurricanes than a port on the east coast. Port exposure, then, may be analyzed using a multiple scenario approach, with a range of values for the applicable climate variables. Measuring port *sensitivity* and *adaptation capacity* generally requires site-specific analyses. By analyzing the impacts of projected changes in regional or even local climate variables and evaluating a port's design criteria in light of those impacts, the sensitivity to those changes can be determined for a port and its assets. Recently constructed infrastructure designed for higher intensity storms, for example, may be considered as less sensitive to a given storm event than infrastructure that is in a state of disrepair already. An assessment of a port's adaptive capacity, taking into account the port system's planning parameters, management flexibility and existing stresses, can reveal obstacles to a port system's ability to cope with climate change impacts. A port with robust planning procedures and more wealth, for example, may be considered to have a higher adaptive capacity than a port that has lesser planning and resources. In 2011, Becker and collaborators made a first attempt at quantifying international seaport adaptive capacity by developing a scoring system based on port authority responses regarding climate adaptation policies currently in place (Becker et al. 2011a).

Because exposure and vulnerability are dynamic (IPCC 2012), varying across spatial and temporal scales, and individual ports are differentially vulnerable and exposed, assessments should be iterative with multiple feedbacks, shaped by people and knowledge (IPCC 2014a), and take a "bottom up" approach by including input from a diverse stakeholder cluster to ensure that the variables representing exposure, sensitivity and adaptive capacity are empirically identified by and important to the stakeholders, rather than presupposed by the researchers or available data (Smit and Wandel 2006).

A concept related to vulnerability, *risk* is a measure of the potential for consequences where something of value is at stake and where the outcome is uncertain (IPCC 2014b). Risk can be quantitatively modeled as $Risk = p(L)$, where L is potential loss and p the probability of occurrence, however, both can be speculative and difficult to measure in the climate-risk context. Risk, in the context of climate change, is often defined similarly to vulnerability (Preston 2012, IPCC 2014a), but with the added component of *probability,* thus making *vulnerability* a component of *risk*.

Resilience, another closely related term with a more positive connotation than *vulnerability*, is defined by the IPCC as "the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation" (IPCC 2014b). The National Academy of Science (The National Academies 2012) and the President of the United States (Obama 2013) define critical infrastructure resilience as, "the ability to prepare, resist, recover, and more successfully adapt to the impacts of adverse events." With *resilience* defined in terms of ability, and *vulnerability* defined in terms of susceptibility, it is tempting to consider them polar opposites (Gallopín 2006), however, resilience can also be considered a broader concept than vulnerability. Most working definitions of resilience involve a process that begins before a hazardous impact, but also includes temporal periods during and after the impact. Resilience, like vulnerability, can also encompass coping with adverse effects from a multitude of hazards in addition to climate change. By increasing our understanding of the distribution of seaport climate vulnerabilities, the overall *resilience* of the MTS may be enhanced.

7.4 CIAV Decision-Support for the Seaport Sector

As port decision makers face climate impact, adaptation, and vulnerability (CIAV)[2] decisions, climate change vulnerability assessments (CCVA), including risk and resilience assessments support those decisions by addressing the "adapt to what" question (IPCC 2014a). The process enables a dialog among stakeholders and practitioners on planning and implementation of adaptation measures to enhance resilience. The Intergovernmental Panel on Climate Change (IPCC) describes vulnerability and risk assessment as "the first step for risk reduction, prevention, and transfer, as well as climate adaptation in the context of extremes." [p. 90] (IPCC 2012) The U.S. NCA considers vulnerability and risk assessment an "especially important" [p. 137] (Melillo et al. 2014) area in consideration of adaptation strategies in the transportation sector. Such assessments can be made at the single-port scale or at the multi-port scale, with each approach having benefits for different types of decision makers.

7.4.1 Single-Port Scale

Among climate change vulnerability, resilience, and risk assessment methods applied to seaports, most efforts to date have been limited in scope to exposure-only assessments (Hanson et al. 2010, Nicholls et al. 2008), or limited in scale to a single port; either as case studies (Koppe et al. 2012, Cox et al. 2013, USDOT 2014, Messner et al. 2013, Chhetri et al. 2014) or as self-assessment tools (NOAA OCM 2015, Semppier et al. 2010, Morris and Sempier 2016).

[2] Climate impact, adaptation, and vulnerability (CIAV) decisions are choices, the results of which are expected to affect or be affected by the interactions of the changing climate with ecological, economic, and social systems.

While single-port scale CCVA inform CIAV decisions within the domain of one port (e.g., Which specific adaptations are recommended for my port?), a CCVA approach that objectively compares the relative vulnerabilities of multiple ports in a region could support CIAV decisions at the multi-port scale (e.g., Which ports in a region are the *most* vulnerable and urgently in need of adaptation?). The hitherto focus on individual port scale assessments presents a challenge for how to describe the *distribution* of climate-vulnerabilities across multiple ports.

7.4.2 Multi-port Scale

At the multi-port scale, an evaluation of *relative* climate-vulnerabilities or the *distribution* of those vulnerabilities among a regional or national set of ports requires standard measures (e.g. indicators, or metrics). Directly immeasurable, concepts such as resilience and vulnerability are instead made operational by mapping them to functions of observable variables called indicators. *Indicators* are measurable, observable quantities that serve as proxies for an aspect of a system that cannot itself be directly, adequately measured (Gallopin 1997, Hinkel 2011). Indicator-based assessment methods, therefore, are generally applied to assess or 'measure' features of a system that are described by theoretical concepts. The indicator-based assessment process of operationalizing immeasurable aspects of a system consists (Hinkel 2011) of two or sometimes three steps: (1) defining the response to be indicated, (2) selecting the indicators, (3) aggregating the indicators (this step is sometimes omitted but necessary to yield a numerical 'score' or create a comparative index). In this section, we investigate examples of indicator-based assessment methods applied to multi-port systems to aid the further development of such methods for the port sector, which can yield benefits including the ability to not only 'measure' immeasurable concepts like vulnerability and resilience, but also to index and compare them across entities.

7.4.3 Factors Considered in Port Resilience Evaluation

The US National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (OCM) along with the federal interagency Committee on the Marine Transportation System (CMTS) produced a port resilience planning web-based tool (NOAA OCM 2015), tailored towards communities undergoing a port expansion or reconstruction, that assembles resilience indicators and their datasets. This web-based prototype tool came online in 2015 with the stated purpose of assisting transportation planners, port infrastructure planners, community planners, and hazard planners to explore resilience considerations and options in developing marine transportation projects. Inspired by and aligned with broader resilience objectives called for in the CMTS's strategic action plan (USCMTS 2011), this tool shows port communities what to look for in resilient freight transportation infrastructure. While the Port Tomorrow resilience planning tool assembles seaport resilience indicators, provides links to their potential data sources, and organizes them with categories and subcategories into a framework for assessing port resilience, the tool stops short of providing a method to normalize and aggregate the indicators into a comparative score.

7.4.4 Assessing Global Port City **Exposure**

One of the few CCVA to comparatively assess multiple ports, the 2010 work by Hanson, Nichols, et al. (Hanson et al. 2010) made some of the first progress towards comparative seaport CCVA by focusing on assessing the *exposure* component of seaport climate-vulnerability. Part of a larger project on Cities and Climate Change that was sponsored by the Organization for Economic Cooperation and Development (OECD), this global screening study assesses the exposure[3] of all 136 international port cities with over one million inhabitants in 2005 to coastal flooding. The analysis considers exposure to present-day extreme water levels (represented by a 100-year flood) as well as six future scenarios (represented by the decade 2070–2080) that include projected changes in sea level and population. The researchers base the methods used on determining the numbers of people who would be exposed to the water level of interest and then using that number to estimate the potential assets exposed within each city. The researchers then rank the cities by number of people exposed and by 2005 U.S. dollar value of assets exposed. These two response variables, i.e. people and dollar value of assets, are semi-empirical quantities rather than theoretical concepts, and as such, the methods involved in this study are not directly analogous to other indicator-based assessment methods. Instead of using indicators to serve as proxies for some immeasurable concept, this study uses indicators to approximate concrete numbers that, due to scale, are difficult to measure.

This study took the form of a Geographic Information System (GIS) elevation-based analysis, after authors (McGranahan et al. 2007). The researchers used 100-year historic flood levels taken from the Dynamic Interactive Vulnerability Assessment (DIVA) database as current extreme water levels to be modeled in GIS for each city. For the future water levels, the researchers calculate two different scenarios, one that considers only natural factors (i.e. a calculated "storm enhancement factor," historic subsidence rates, and sea level rise (SLR)), and another that adds to those factors one representing anthropogenic subsidence.

For current population, the study takes the ambient population distribution estimates from LandScan 2002 (Bright and Coleman 2003) for each city, delimited by city extents from post code data. The postcodes are taken from geocoding data and, for cities in the USA, from Metropolitan Statistical Areas (MSAs) from Census

[3] Exposure refers to the nature and extent to which a system is subjected to a source of harm, taking no account of any defenses or other adaptation.

data. The authors resample the 1 km LandScan 2002 data to 30 m for all cities in the US and UK and resampled to 100 m for the remaining cities. To determine population distribution by elevation, the authors use 90 m resolution topographic data from the Shuttle Radar Topography Mission (SRTM) for most cities, 30 m SRTM data for the US, and a 10 m Digital Elevation Model (DEM) provided by Infoterra for the UK. The authors then overlay each LandScan population distribution over the relevant Digital Terrain Model (DTM), yielding for each city a map of geographical cells with defined population and elevation. From these maps, the authors are able to isolate total population within 1 m vertical bands of elevation. To represent future population, the authors start with baseline population projections from the OECD ENV-Linkages model, which itself is based on United Nations (UN) medium variant projections to 2050. To bring these projections to 2070, the authors extrapolate them forward using national growth rates and UN projected rates of urbanization.

To indicate the dollar value of assets, the researchers use what they describe as a "widely used assumption in the insurance industry" (Hanson et al. 2010, 92) (p 92) that as urban areas are typically more affluent than rural areas, each person in a city has assets that are 5 times the national Gross Domestic Product (GDP). This simple calculation is based on the national per capita GDP Purchasing Power Parity (PPP) values for 2005 from the International Monetary Fund (IMF) database. To indicate future GDP, the study uses OECD baseline projections to 2075. To find the total value of assets exposed then, the researchers take the number of people exposed (from the GIS maps described above) and multiply that number by a country's GDP PPP times five.

Using the indicators described above, and organized in Table 7.1, this study is ultimately able to produce rankings of port cities exposed to coastal flooding by number of people and by dollar value of assets exposed to extreme water levels in 2005 and for projected extreme water levels in 2075.

7.4.5 *Assessing Regional Port* **Interdependency** *Vulnerabilities*

Another example of CCVA that extends beyond the single-port scale is the 2013 work by Hsieh et al. that examines the vulnerability of port failures from an interdependency perspective using four commercial ports in Taiwan as empirical case studies (Hsieh et al. 2013). The method determines factors vulnerable to disasters by reviewing literature and conducting an in-depth interview process with port experts; in this way, the researchers developed 14 'vulnerable factors' that can be considered similar to our described indicators (Berle et al. 2011).

To develop the 14 indicators, the authors held a series of discussions in open participatory meetings. Eleven experts participated, including port officials, government officials, planners, and scholars. The discussions classified the indicators into four categories: accessibility, capability, operational efficiency, and industrial cluster/energy supply, as shown in Table 7.2. The process to determine weights for the indicators followed the analytic network process (ANP) of Jharkharia and

Table 7.1 Indicators, categories and data sources used in (Hanson et al. 2010)

Indicator categories	Indicator sub-categories	Indicators	Data source
Elevation	Elevation	elevation	Shuttle Radar Topography Mission (SRTM)
Population	Population	population distribution	Landscan 2002
Future Population	Future Population	Projected Population in 2075	OECD ENV-Linkages Model
	Projected Urbanization Rate (assumed uniform within country)	2005–2030 trends extrapolated to 2075, assuming that urbanization rates will saturate at 90%, except where it is already larger than this value (e.g. in special cases like Hong Kong)	UN projected urbanization rates 2005–2030 (are then extrapolated to 2075)
Current Water Level	Current Water Level	100 yr. storm surge	DIVA
Future Water Level	SLR	assumes a homogenous global rise of 0.5 m by 2070	assumed from lit.
	Anthropogenic Subsidence	assumes uniform 0.5 m decline in land level (from 2005 to 2070) in port cities located in deltas	assumed
	Natural Subsidence	Annual Rate of subsidence extrapolated to 2070	used annual sub. Rate from DIVA
	Storm Enhancement Factor	10% increase in extreme water level assumed for cities exposed to TC, 10% increase assumed for cities bet. 45 and 70 deg. latitude which are assumed exposed to Extra-TC	CHRR (Columbia), historical TC tracks, Munich Re
Value of Assets	Value of Assets	national per capita GDP PPP (assuming each person in a city has assets 5 x annual GDP per capita)	www.imf.org
Future Value of Assets	Future Value of Assets	Projected GDP per capita	OECD Baseline projections to 2075

Shankar (2007) (Jharkharia and Shankar 2007), and involved constructing an impact matrix via fuzzy cognitive maps (FCMs) developed and evaluated during these participatory meetings. The impact matrix represents magnitudes of causal effects of each indicator compared to every other indicator.

To standardize the indicators, the experts completed a questionnaire that had them identify threshold values for each indicator. The researchers provided a scale from 0–4, with 0 indicating that the port can operate normally, and 1–4 indicating that the port would experience slight, average, significant effects, and complete port

Table 7.2 Indicators, categories, and data sources used in (Hsieh et al. 2013)

Indicator categories	Indicators	Data source
Accessibility	Ground access system (%)	GIS maps
	Travel time (minute)	GIS maps
	Shipping route density (lines)	port annual statistics overviews
Capability	Gantry crane capacity (TEUs)	Ministry of Transportation and Communications
	Facility supportability (%)	port annual statistics overviews
	Wharf productivity (10^3 tons/meter)	Ministry of Transportation and Communications
Operational Efficiency	EDI connectivity (%)	Ministry of Transportation and Communications
	Turnaround time (hr)	Ministry of Transportation and Communications
	Labor productivity (tons/person)	port annual statistics overviews
	Berth occupancy rate (%)	port annual statistics overviews
Industrial Cluster/Energy Supply	Investment growth (10^9 NTD[a])	national industry, commerce, and service census
	FTZ business volume (10^9 NTD)	national industry, commerce, and service census
	Electric power supply (%)	GIS maps
	Gas supply (%)	GIS maps

[a]*NTD* New Taiwan Dollars

failure, respectively. Using this scale, the experts identified a threshold value (i.*E. minimum* or maximum value, depending upon whether the indicator indicates vulnerability or competitiveness) for each indicator that would lead the port to each of the five results described in the scale 0–4. The researchers used the Delphi method during three rounds, allowing the experts to revise their earlier answers in light of the replies of other members of their panel and achieve consensus. Table 7.3 shows the standardized indicators (called "Vulnerable factors"), their units, and their threshold values.

The data for the indicators come from published statistics, literature, and GIS maps. Table 7.2 shows the specific data source for each of the 14 indicators. To score a port's vulnerability, the researchers standardize a port's raw indicator data using Table 7.3, then sum the standardized indicators multiplied by their weights to produce a total vulnerability score. The results for the 4 Taiwanese case study ports are shown in Table 7.4.

In addition to the vulnerability assessment method herein described, Hsieh et al. also conducted an interdependency analysis to determine how strongly each indicator affects and is affected by the other indicators of the port system. This analysis uses groups of experts who fill out a matrix form during an iterative Delphi-style process, similar to that used during the first stages of this project.

Table 7.3 Standardized indicators showing threshold values from (Hsieh et al. 2013)

Vulnerable factors		Rating				
		0	1	2	3	4
(1)	Ground access system (%)	>90	90–80	80–50	50–20	<20
(2)	Travel time (minute)	<90	90–120	120–150	150–180	>180
(3)	Shipping route density (lines)	<15	15–100	100–200	200–300	>300
(4)	Gantry crane capacity (TEUs*)	>90	90–70	70–50	50–35	<35
(5)	Facility supportability (%)	>80	80–70	70–50	50–40	<40
(6)	Wharf productivity (103 tons/ meter)	>5	5–4	4–2	2–1.5	<1.5
(7)	EDI connectivity (%)	>90	90–80	80–50	50–20	<20
(8)	Turnaround time (hr)	<24	24–36	36–48	48–72	>72
(9)	Labor productivity (tons/person)	>350	350–250	250–150	150–100	<100
(10)	Berth occupancy rate (%)	>70	70–50	50–30	30–10	<10
(11)	Investment growth (109 NTD**)	>10	10–8	8–4	4–2	<2
(12)	FTZ business volume (109 NTD**)	>10	10–8	8–4	4–2	<2
(13)	Electric power supply (%)	>90	90–80	80–50	50–20	<20
(14)	Gas supply (%)	>50	50–30	30–20	20–5	<5

Table 7.4 Results of port vulnerability analysis from (Hsieh et al. 2013)

	Score of vulnerable factors	Keelung	Taipei	Taichung	Kaohsiung
(1)	Ground access system	3	2	2	1
(2)	Travel time	2	1	0	0
(3)	Shipping route density	1	1	1	4
(4)	Gantry crane capacity	3	3	1	0
(5)	Facility supportability	0	3	2	0
(6)	Wharf productivity	0	2	0	1
(7)	EDI connectivity	1	1	1	1
(8)	Turnaround time	0	1	1	1
(9)	Labor productivity	0	0	1	1
(10)	Berth occupancy rate	3	1	2	2
(11)	Investment growth	4	2	0	0
(12)	FTZ business volume	4	1	0	0
(13)	Electric power supply	2	0	1	0
(14)	Gas supply	1	0	0	0
Port	vulnerability	1.6131	1.8063	0.8746	0.7724

7.4.6 *Assessing Relative Port* Performance

At the multi-port, MTS scale, CCVA have been sparse. Indicator-based multi-port assessments to date have tended to focus on port *performance* rather than *vulnerabilities* or *resilience.* Here, we investigate some of the methods used to assess relative port *performance* in an effort to inform new CCVA methods at the multi-port scale.

7.4.7 *Port Performance Indicators: Selection and Measurement (PPRISM)*

Carried out from 2010 to 2011 by the European Seaports Organization (ESPO) and co-funded by the European Commission, the Port Performance Indicators: Selection and Measurement (PPRISM) program was designed to take a first step towards establishing a culture of performance measurement in European ports by identifying a set of relevant and feasible performance indicators for the European port system. The aim of this project was to develop indicators that allow the port industry to measure, assess, and communicate the impact of the European port system on society, the environment, and the economy. Although PPRISM does document equations (ESPO 2011) used to aggregate numbers used for individual indicators, this study does not aggregate the indicators themselves into a total performance score. The future plans for PPRISM include the establishment of a Port Sector Performance Dashboard (as part of a European Port Observatory website) that will not publish or compare interport performance, but illustrate the performance of the whole European system of ports.

The indicator selection process began with input from five European Universities: University of the Aegean, Institute of Transport and Maritime Management Antwerp, Eindhoven University of Technology, Vrije Universiteit Brussel, and Cardiff University. These academic partners came up with 159 port performance indicators based on a literature review and industry current practices and organized them under the following five categories: Market Trends, Logistic Chain and Operations, Environmental Indicators, Socio-economic Indicators, and Governance Indicators. The academic partners excluded indicators that did not fulfill one of the following criteria (ESPO 2010):

P: Policy relevance – Monitor the key outcomes of strategies, policies and legislation and measure progress towards policy goals. Provides information to a level appropriate for policy decision – making.

I: Informative – Supplies relevant information with respect to the port's activities.

M: Measurable – Is readily available or made available at a response cost/benefit ratio. Updated at regular intervals in accordance with reliable procedures.

R: Representative – Gives clear information and is simple to interpret. Accessible, publicly appealing and therefore likely to meet acceptance.

F: Feasible / Practical – Requires limited numbers of parameters to be established. Uses existing data and information wherever possible. Simple to monitor.

Following the academic pre-selection process, the 159 indicators were assessed by ESPO members. ESPO organized four special workshop sessions for this purpose in combination with its Technical Committee meetings. During these workshops, ESPO members screened the pre-selected indicators and discussed their proposed definitions and calculation methods with the academic partners. ESPO members considered and provided qualitative feedback on the data availability and relevance of the proposed indictors. Additionally, ESPO members provided quantitative feedback on the feasibility and acceptability of each indicator by using a five point Linkert-style scale during two rounds, following the Delphi methodology.[4] The first round of this Delphi-style assessment process by ESPO members narrowed the 159 indicators down to 39. The second round with the modified indicators resulted in additional indicators, adjustments to indicator definitions and calculation formulas, renamed indicators, and produced a new list of 45 indicators.

The four rounds involved in the Delphi-style indicator assessment included only internal stakeholders (i.e. representatives of the European port authorities). In an effort to increase the validity and reliability of the work, the scope was then expanded to include external stakeholders, targeting a "representative external stakeholder response panel" (ESPO 2011) to include port users, government, and academics. This external stakeholder assessment made use of an online survey that was freely available without restrictions on who was invited to participate. The survey was advertised in social media, specialized presses, and personal networks and remained open for 4 months (February–May 2011). This external stakeholder assessment helped to narrow the list of indicators further to 42.

The results of the internal and external stakeholder assessments guided the final choice of 14 indicators that were then tested in a pilot phase. The 42 indicators were narrowed down to 14 (Table 7.5) through a process of weighing stakeholders' acceptance vs the feasibility of implementation of each indicator.

The pilot consisted of an EU-wide project to test the feasibility of the 14 selected indicators, with the intent to uncover the real-world availability of data and the willingness of port authorities to provide data. For the pilot study, the PPRISM group sent an electronic form to all port authorities associated with ESPO accompanied by an explanatory letter from ESPO Secretary General Patrick Verhoeven and received back a total of 58 forms fully or partially filled out. The pilot revealed problems with data availability, unclear data requests, and port participation. Given that data provision is voluntary, and hence, the number of ports submitting could fluctuate from year to year, the pilot study recommended that, at least for the initial stages of any

[4] The Delphi method is an iterative, multistage response process designed to generate expert consensus.

Table 7.5 Findings and conclusions for each piloted indicator (ESPO 2012)

Indicators	Pilot result	Next steps
1. Maritime traffic	Relevant and feasible	Building a "time series" mainly focusing on the relative changes in traffic volumes over time. A three dimensional approach is suggested with respect to the dimension of 'time', (quarterly figures), of 'commodity'[total throughput plus 5 categories of cargoes plus passenger traffic (7 in total)] and 'geography'(all European ports)
2. Call size	Relevant and feasible	Building a "time series" mainly focusing on the relative changes in traffic volumes over time. A three dimensional approach is suggested with respect to the dimension of 'time', (yearly figures), of 'commodity'[total throughput plus 5 categories of cargoes plus passenger traffic (7 in total)] and 'geography'(all European ports)
3. Employment (Direct)	Relevant and feasible	Getting data from a larger number of ports
4. Added value (Direct)	Relevant and feasible	Getting data from a larger number of ports
5. Carbon footprint	Relevant and feasible	Make Tool available to port associations and authorities. Provide training support where requested.
6. Total water consumption	Relevant and feasible	
7. Amount of waste	Relevant and feasible	
8. Environmental management	Relevant and feasible	Promote using Tool (see above) and populate from SDM and PERS responses.
9. Maritime connectivity	Relevant and feasible	Building a 'time series' to monitor maritime connectivity over time.
10. Intermodal connectivity	Relevant and feasible	Getting data from a larger number of European ports.
11. Quality of customs procedures	Relevant and feasible	This indicator can be substituted by something more detailed in the medium run. Until then, this is the best available indicator.
12. Integration of port cluster	Relevant and feasible	Revision of criteria used. The need to reduce the number of criteria is already anticipated. More detailed info for each criteria will be asked. Efforts to standardize and collect quantitative data as well. In the long run the objective is to measure the efficiency of a PAs initiatives related to the respective indicators.
13. Reporting Corporate and Social Responsibility	Relevant and feasible	
14. Autonomous management	Relevant and feasible	

port performance dashboard, reporting data in the form of trends rather than single values is the best approach. The results of the pilot study are shown in Table 7.5.

Upon conclusion of the pilot study, the PPRISM project group published its executive report (ESPO 2012), with the recommendation that the development of European Ports Observatory be phased in over time, starting small. Though a printed version of a Dashboard was presented at the 2012 ESPO Conference in Sopot, Poland, the current status of the dashboard remains unclear.

7.4.8 USCMTS Marine Transportation System Performance Measures

The World Association for Waterborne Transport Infrastructure (PIANC) report, *Performance Measures for Inland Waterways Transport (*PIANC Inland Navigation Commission 2010*)*, identifies three general purposes for performance measures (operational, informational, referential) and nine thematic areas (infrastructure, ports, environment, fleet and vehicles, cargo and passengers, information and communication, economic development, safety, and security). Building upon the PIANC report and aiming to create an initial picture of the overall state of the U.S. MTS using authoritative data, the United States Committee on the Marine Transportation System (USCMTS) Research and Development Integrated Action Team in 2015 published a compilation of MTS *performance measures* (USCMTS 2015) developed from publicly available data sources. Serving as standard metrics, such indicators allow standardized comparison of the components of port *performance* including; Economic Benefits to the Nation, Capacity and Reliability, Safety and Security, Environmental Stewardship, and Resilience.

While the USCMTS study suggests two "Resilience Performance Measures," (i.e., *Age of Federally Owned and Operated Navigation Locks*, and *Physical Condition Rating of Critical Coastal Navigation Infrastructure owned by USACE*[5]), these measures do not consider private, state, or locally owned container terminals or port facilities, and the authors conclude that more work is needed to capture the concept of port or MTS resilience using standard metrics. Table 7.6 compares the indicator selection and aggregation methods of the aforementioned indicator-based seaport assessments.

7.5 Discussion

To date, there are relatively few examples of multi-port assessments. The approaches discussed in this chapter, and summarized in Table 7.6, tend to lean heavily on expert judgement in the selection and evaluation for indicators of climate vulnerability or focus exclusively on the "exposure" aspect of vulnerability.

Worth note is the use of indicators to develop a score or rating of climate vulnerability (or resilience). Such assessment may be welcome or rejected, depending on the goals and objectives of the audience. For example, a high "vulnerability" score

[5] United States Army Corps of Engineers.

Table 7.6 Examples of multi-port, indicator-based assessments

Study	Response Indicated	Indicator Selection Method	Indicator Aggregation Method
PPRISM	Port performance	(i) Academic pre-selection	Not aggregated
		(ii) Delphi Method with internal stakeholders	
		(iii) Delphi Method with external stakeholders	
USCMTS Performance Measures	Port performance	Internal review: An ideal MTS performance measure would be collected locally, using the same method across all areas of responsibility, so that state, regional, and national summaries could be easily compiled for comparison.	Not aggregated
Nichols and Hanson et al.	Coastal flood exposure measured in number of people and dollar value of assets	Response variables are semi-empirical quantities rather than theoretical concepts.	Does not involve selecting and aggregating indicators; rather it involves a more straightforward calculation of the responses.
Hsieh et al.	Port interdependency vulnerability	(i) Participatory discussion process with experts	(i) Experts develop weights via analytic network process (ANP)
		(ii) Delphi method with experts	(ii) Raw indicator data is standardized, weighted, and summed to yield a vulnerability score
NOAA Port Tomorrow	Port resilience	Indicator selection is led by a guiding question for each indicator subcategory	Not aggregated

may help a port petition a funding agent to build a case for needed resilience investments. On the other hand, a high score could also leave a port at a competitive disadvantage if tenants perceive higher levels of storm risk. Thus, while aggregations, scores, and rankings may be desired by regional or national-level decision makers, creating multi-port assessment tools is not without controversy.

That said, such tools *can* help inform the decision-making process. And, as demand for climate-critical resources (both funding and materials) increases, the need to better understand relative vulnerability of coastal systems, such as ports, will also increase. Our review of the literature suggests a need for better tools that can be used to gain an objective understanding of various aspects of port vulnerability. Although expert judgement will likely be necessary to a certain extent, due to the inherent difficulty of measuring and quantifying fuzzy concepts such as "adaptive capacity," publicly available data (e.g., historical storm tracks, types of cargo handled, throughput) can also be leveraged to help decision makers gain a better sense of which areas are more vulnerable, in what ways, and how this vulnerability might be reduced.

7.6 Conclusion

Seaports are critical to global trade and national security, yet sit on the front-line for extreme coastal weather and climate impacts, and such impacts are projected to worsen globally. As port decision-makers wrestle with the myriad of climate adaptation options (including the option of making no adaptations at all), their CIAV decisions can and should be supported with data. For CIAV decision-support, the first step often involves assessing vulnerabilities. For an individual seaport, this process tends to take the shape of CCVA, either as a participatory self-assessment, or as a site-specific case study. For multiple port systems, however, we suggest an opportunity exists for further research and development of standardized, comparative CCVA methods for seaports and the marine transportation system, with the objective of supporting CIAV decisions with information products that allow decision makers to compare mechanisms and drivers of climate change across multiple ports.

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