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Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index

ABSTRACT

Climate change, which is largely caused by anthropogenic emissions of CO2, is one of the main challenges facing humankind today. In this context, and from the logistics point of view, ports are critical infrastructures not only because of their great vulnerability to such adverse phenomena, but also because of their key importance in global supply chains. We therefore need indicators that will allow us to both determine a port's resilience to the various challenges posed by climate change and take preventive actions to ensure the port can function correctly over time. This study presents a port resilience index (PRI), which, unlike existing indices, considers all stakeholders to determine the level of operational resilience of port processes. The index was validated in the external port of A Coruña (Galicia), chosen because of its especially adverse conditions and because in Spain, the effects of climate change are likely to be especially damaging. The results show that this port has an overall PRI of 52% and that its infrastructure and facilities and operational environment against the climate change challenge are especially sensitive. Analysis of the different factors of resilience allows port managers and policy makers to focus their actions on the factors that have the greatest impact on resilience. This should lead to better use of resources and more efficient contingency plans.

Key words

Climate change, resilience, ports, value chains, composite index, stakeholders

1. INTRODUCTION

Climate change, largely caused by anthropogenic emissions of CO2, is one of the main challenges facing humankind today (Howard-Grenville et al., 2014). However, contrary to what is usually believed, it is not a disruptive phenomenon but a gradual increase in the frequency and intensity of extreme weather events such as storms, droughts or flooding (Schaeffer et al., 2012). Many authors state that this process has already begun and that it will jeopardize global trading networks as we know them today (Natural Hazards, 2014).

In this context, seaports are especially critical in their role as logistic nodes, not only because they are vulnerable to climate change, but also because of their enormous importance in global supply chains. They are vulnerable because their location makes them especially exposed to adverse climate phenomena (Becker et al. 2013; Xiao et al., 2015; O'Keeffe et al., 2016). More frequent and more intense rainfall and storms, for example, may affect ports' operability. Furthermore, "slow start" climate changes, such as rising sea levels, stronger waves, or increased salinity—which exacerbates corrosion—also have a significant negative impact on this type of infrastructure (IPCC, 2012). In fact, ports play a key role in international supply chains. They are nodes for transport and logistics, and they form part of complex, international logistics systems. Of goods traded worldwide, 80-90% are carried by sea (IMO, 2012; Garcia-Alonso et al., 2020), and a 4% annual increase in maritime trade is forecast over the next five years (UNCTAD, 2019). However, these same reports give warnings about the vulnerability of port infrastructures to changing conditions in oceans and the atmosphere, as well as to huge global economic losses if port operations must be interrupted (Ng et al., 2019). It is therefore important to increase the adaptability of port systems to future disruptive events caused by climate change. Both port authorities and governments need to rethink the design and operations of port infrastructure if they are to successfully cope with environmental challenges (Molavi et al., 2019). However, to achieve any type of improved performance, an indicator is needed to ascertain the resilience of ports—that is, their capacity to absorb and recover from a damaging event—to the impacts of climate change (Ng et al., 2019).

It is surprising, however, the scarcity of empirical studies on the design of resilience indices for port infrastructures, which has been rather neglected in the field, and their lack of validation (Ng et al., 2018; Yang et al., 2017). In addition, most previous studies evaluating port vulnerability and risk in the face of climate change are partial, focusing on specific climatological elements (Camus et al., 2019; Sierra et al., 2017; Becker et al., 2015) or on just some of the stakeholders (Becker et al., 2012; Ng et al., 2018). Others are included within excessively broad studies (e.g., cities, shoreline analyses, etc.) that cannot provide specific insights into the improvement of port facilities (e.g., Becker et al., 2012; McIntosh and Becker, 2017; Izaguirre et al., 2020b) or establish a methodological framework for the analysis of port resilience (Izaguirre et al., 2020a).

In this context, our study proposes a methodology for drawing up an integrated port resilience index (PRI) that covers the aforementioned limitations, with indicators that focus specifically on the port operations, are of a quantitative nature, and include all the stakeholders involved in port activities. In fact, we focus specifically on the "operational resilience," which is the term used in this paper, to stress the need to "make the system able to absorb the impact of an event without losing its operational capacity" (Alderson et al., 2015). In addition, this index was validated by applying it to a real case: the external port in A Coruña (Galicia, Spain).

The article has five sections. After this introduction, we give a brief description of the state of the art in this field. In the third section, we describe the methodology used for drawing up the resilience index. We then describe the results of the case study (section four), and, finally, we draw some conclusions and suggest possible avenues for future research.

2. LITERATURE REVIEW

2.1. Climate change and resilience

Climate change will undoubtedly trigger disruptive changes in processes used today, as well as raise new challenges, which will have to be faced by economic and social agents (Howard-Grenville et al., 2014). Coastal communities have been identified as particularly vulnerable to climate change, hence the need for enhancing resilience in these environments so they can adequately adapt to climate risks such as sea level rises and extreme weather events (Greenan et al., 2019). Facing these risks has important management and policy implications for coastal communities of all kinds. Therefore, it is vital to start developing tools that help all stakeholders understand how the potential consequences of climate change could affect their communities (Colburn et al., 2016).

To assist in this goal, the effects of climate change on port resilience are studied from a dual perspective—mitigation and adaptation. Whereas mitigation aims to prevent climate change by reducing greenhouse gas emissions, adaptation assesses the likely consequences of these phenomena and aims to increase the capacity for adaptation and recovery through proactive responses to protect infrastructure considered critical (Ng et al., 2019). Therefore, in adaptation, the resilience of ports and the need to protect them (making them adaptable) are of special importance because of their key role as supply chain nodes and their vulnerability to climate change (Ng et al., 2019; Camus et al., 2019).

The concept of resilience was first used by Holling (1973) in the field of ecology as a tool for assessing the capacity of ecological systems to absorb changes and disturbances while maintaining the relationships between populations or status variables. However, since the publication of that seminal work, this concept has spread to many different areas (Mayunga, 2007), for evaluating disasters in the short term (Bruneau et al., 2003; Rose, 2004) or for long-term phenomena such as climate change (Djalante and Thomalla, 2010; Aldunce et al., 2015). Examples of application of this concept can be found in social, community, and ecological systems (e.g., Sharifi and Yamagata, 2014; Meerow et al., 2016); risk management (e.g., Alexander, 2013; Aldunce et al., 2015); transport systems; economic systems; and organizational management (Fang et Al., 2016). However, undoubtedly, one of the fields in which this term has been most widely adopted is climate change (Nickson, et al., 2011). Various organizations stress the importance of resilience and share the same definition. The Intergovernmental Panel on Climate Change (IPCC, 2012), for example, defines resilience as “the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.”

The United Nations (UN), in the Report on the World Conference on Disaster Risk Reduction at Hyogo (UN-ISDR, 2005), defines resilience as “the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures.” Both the UN and the US Presidential Policy Directive (U.S. President, 2013) not only refer to the capacity for resisting and recovering quickly from interruptions, but also include in the definition of resilience the need for systems to be prepared for and to adapt to changing conditions. This has given rise to the term “operational resilience,” to stress the need to “make the system able to absorb the impact of an event without losing its operational capacity” (Alderson et al., 2015). We adopt this term explicitly to assess the capacity of a system to anticipate problems and adapt its behavior to maintain continued functions (or operations) in the presence of interruptions. Xiao et al. (2015) stated that damage caused by disasters could be prevented or alleviated by making appropriate investments. However, investment in ports for the purpose of preventing disasters is a matter that has not been widely studied because of its complexity and the huge challenges involved. Faced with this situation and given that it seems clear that certain disruptions are inevitable, organizations must learn to adapt their routines and operating procedures to become resilient (Hohenstein et al., 2015; Scholten et al., 2019).

2.2. Resilience indices: current development and shortcomings for application to ports

A composite index is a mathematical aggregation of a set of indicators used to summarize the characteristics of a system, community, or society with regard to what is aimed to be measured (Salvati and Carlucci, 2014; McIntosh and Becker, 2017). Furthermore, as indicators allow for the operationalization of systems' observable variables, this type of indicator-based evaluation method proves to be useful when the concepts to be measured are not of directly quantifiable nature (McIntosh and Becker, 2019). This is precisely the case with the concept of resilience: It cannot be measured directly but can be operationalized "by mapping it to functions of observable variables called indicators" (McIntosh and Becker, 2017). In fact, although resilience is a relatively new term, its increasing development is clear from the multitude of methods and indices, both quantitative and qualitative, that have been developed to evaluate it (Jordan and Javernick-Will 2013). Nonetheless, some weaknesses must be considered when building indicators because they might collapse or obscure important information that is pivotal to properly assess the diverse characteristics of a system (Davis et al., 2015). Such weaknesses are the result of stakeholder negotiations, with the possibility of being biased to those most powerful interest groups. Furthermore, they could cause overreliance on a sole variable (with its defects to explain complex relationships) while ignoring others with, at least, the same importance (e.g., overreliance on the use of GDP to measure the wealth of a country). However, most importantly, it is almost impossible to discern the causal effects of the characteristic being measured because they become intertwined with a myriad of related characteristics from which they cannot be isolated (Davis et al., 2015). By building a composite index that included a representative sample of the different stakeholder groups, we thus aimed to alleviate these problems.

However, in spite of the importance to coastal communities, supply chains, and global, national, and regional economies, to date, only a limited number of studies have investigated the link between the potential effects of climate change and their influence on port infrastructure. Not only is there a small number of studies, but most of them are theoretical or adopt a partial view, evaluating only specific climatological elements. For example, there are studies on rising sea levels (Camus et al., 2019; Sierra et al., 2017) or the roughness and height of waves (Sierra et al., 2017) that cover the topic of port resilience from those angles. However, authors such as McIntosh and Becker (2019) have suggested that by evaluating a port's adaptability through its exposure to a varied range of impacts, a more complete image of the mechanisms and drivers of a port's climate vulnerability can be obtained.

We found enough contributions related to port resilience on a community level (Mayunga, 2007; Summers et al., 2017) or among coastal communities (Orencio and Fujii, 2013; Smith et al., 2019), but only a few studies have responded to the call for the development of indicators focused on port infrastructures (Laxe et al., 2017). Among them, Izaguirre et al. (2020b) identified a number of hazards in global port operations, including changes in waves, storm surge, wind, or precipitation. Monioudi et al. (2018) proposed a methodology focused on establishing minimum thresholds that guarantee the operability of port infrastructures. Mutombo and Ölçcer (2017) assessed the exposure to climate risk of port infrastructures through a questionnaire based on a matrix in which port processes and possible extreme climatic situations are crossed, which enables identification of high-risk scenarios. Finally, it is worth highlighting the work of Izaguirre et al. (2020a). These authors suggested a multilevel methodology for conducting climate change risk assessments in ports. This methodology provides stakeholders and policy makers with information to identify hotspots and climate risk adaptation strategies. The authors proposed three levels of risk assessment: i) preliminary analysis, ii) perceived risk analysis, and iii) high-resolution assessment. Starting from a qualitative analysis at the first level, the methodology escalates levels according to the needs detected.

This shortage of indicators may partly be due to the fact that resilience to disasters is a complex interaction involving various factors, each with its own forms and functions (Cutter et al., 2014). Indicators are needed to quantify and simplify all these aspects.

In general, resilience to disasters is measured using semi-quantitative approaches (Hosseini et al., 2016), which allow for the development of composite indices that summarize the complex or multidimensional characteristics of a community or infrastructure. Although we located some empirical studies related to the measurement of resilience in the field of communities and coastal areas in a global context that include ports (Stephenson et al., 2017, 2019; Greenan et al., 2019; Foley et al., 2020), we did not identify composite indices that are exclusive to port areas. In this sense, we conceptualize *operational resilience* as the dynamic capacity of a system to proactively adapt to changes by involving the individuals, groups, and subsystems that compose it (Kamalahmadi and Parast, 2016). This capacity allows the system to absorb the impact of adverse events, such as those caused by climate change, without compromising the operational capacity of the port (Alderson et al., 2015). Nonetheless, previous research was of special importance to establish the main dimensions in which the different resilience factors are grouped in our study. Kusumastuti et al. (2014) developed a resilience index toward natural disasters by identifying six dimensions of resilience: social, community capacity, economic, institutional, infrastructure, and hazard. For their part, Shaw and the IEDM Team (2009) established five dimensions of resilience: physical, social, economic, institutional, and natural. Other authors, such as Summers et al. (2017) and Smith et al. (2019), grouped coastal resilience factors into the following five dimensions: natural environment, society, built environment, governance, and risk.

The use of such composite indices offers important advantages for professionals, allowing them to pass on information in a simple fashion to both experts and non-experts (e.g., Yoon et al., 2016). In fact, several indices are now habitually used in research on disasters and threats: Some well-known examples are the Social Vulnerability Index (SOVI), the Disaster Risk Index (DRI), the Earthquake Disaster Risk Index (EDRI), the Community Disaster Resilience Index (CDRI), and the Coastal Infrastructure Vulnerability Index (CIVI). It might seem easy to define composite indices because they are now widely used (Greco et al., 2019), but there is no standard definition in the literature. Saisana and Tarantola (2002, p. 5) suggested that composite indices are “based on sub-indicators that have no common meaningful unit of measurement and there is no obvious way of weighting these sub-indicators." Freudenberg (2003, p. 5) defined composite indices as "aggregated indices of individual indicators." In the first OECD manual on building composite indices, Nardo et al. (2005, p. 8) stated that a composite index "is formed when individual indicators are compiled into a single index, on the basis of an underlying model of the multidimensional concept being measured."

However, this great development reveals the lack of consensus on quantifying measures and developing indicators for disaster resilience. In fact, there are doubts about whether certain indicators will really be useful for representing the results or processes of disaster resilience (Prior and Hagmann, 2014), especially in facilities such as ports, for which there are no indices. Some of the most important limitations detected in the literature review are the following:

i. Most of the evaluations observed are qualitative, so they can be used as guidelines for defining resilient systems, but the description given is not sufficient for policy makers who need an explanation to maximize the efficient allocation of resources (Cutter et al., 2014).

ii. The quantitative evaluations found also have serious limitations: Although they are useful for describing the structures or characteristics of particular systems, they generally use inappropriate assumptions when evaluating complex, highly connected systems in which the structures and characteristics are not necessarily specified (Dessavre et al., 2016).

iii. Another weakness pointed out by both academics and policy makers is the fact that many of these indicators only present a biased view of some of the stakeholders. Authors such as Bryson (2004) and Few et al. (2007), among others, have emphasized the importance of including stakeholders' perspectives in the development of resilience in general.

iv. Finally, another of the main problems arising with many of the resilience indicators evaluated in the literature is the lack of validation. Prior studies acknowledge the importance of validation but have not tested a methodology for verifying if quantitative results can really represent a system's disaster preparedness (e.g., Mayunga, 2007).

In this context, our study proposes a renewed methodology for drawing up a PRI that, being quantitative in nature and including all the stakeholders involved in the port activities, is able to overcome the abovementioned limitations and explicitly answers the following research questions:

> ***Question 1.*** *What is the most appropriate weighting system for evaluating operational resilience in an external port (the most vulnerable to climate change effects)?*
>
> ***Question 2.*** *To what extent do the dimensions and criteria of the proposed PRI determine measurable results on community resilience?*

We used a case study focusing on the external port in A Coruña to test the validity of the proposed resilience index. We chose this case study because of its special adverse conditions: a young port in the open sea located in Spain, a country that will be especially affected by climate change.

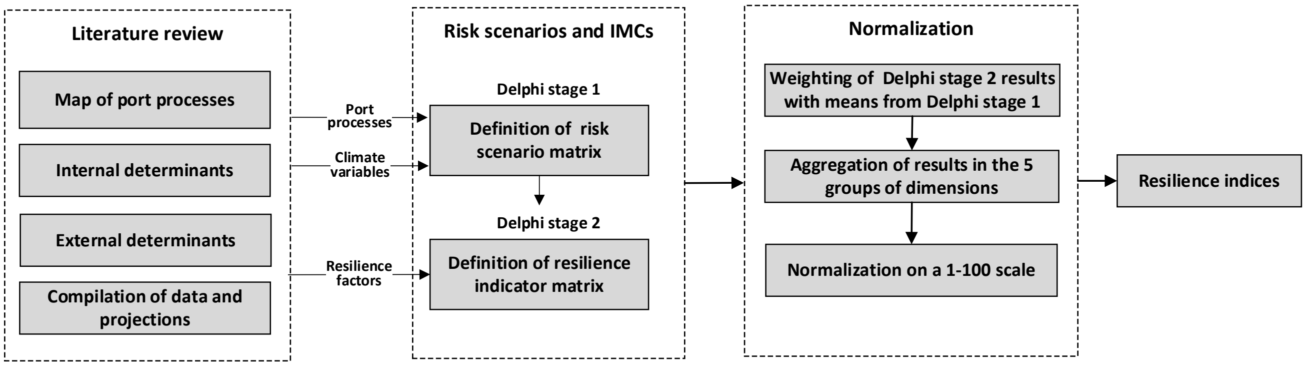
3. DEVELOPMENT OF A PORT RESILIENCE INDEX

Our goal in developing the PRI is to provide stakeholders, managers, and policy makers with a tool that allows them to assess the adaptability of ports in the face of potential operational risk scenarios triggered by “extreme” climatic and oceanic-meteorological elements as a consequence of climate change.

Rather than partial, not port-specific, or qualitative, our construct aims to create a comprehensive, quantitative method to assess the operational resilience of ports. With the objective of measuring this operational resilience, our methodology proposes, in the first stage, the identification of both the possible climatic and ocean-meteorological risks derived from climate change and the critical processes to maintain the operability of a port infrastructure. By crossing these data, a series of risk scenarios that could compromise the continuity of port processes is established. In the second phase, we propose to analyze the capacity of a series of resilience factors, grouped into five dimensions of four factors each, to moderate the identified risk scenarios. The result is a composite index that provides stakeholders, managers, and policy makers with a decision-making tool, allowing them, on the one hand, to identify the areas in which improvement is necessary and, on the other, to establish which measures can have a greater impact on reducing the risk of business interruption.

We chose to design a composite index with indicators because such a tool offers information in a simple way, making it easy to understand for both professionals and non-professionals (Yoon et al., 2016). The methodology we propose is structured as follows (Figure 1):

Figure 1. Methodological design for the PRI



In the initial stage, by means of (a) a thorough literature review, (b) advice from experts, and (c) inclusion of the perspectives of port stakeholders, both internal and external, we established the nature of the index and selected three sets of variables to be used throughout the index construction: (i) variables related to critical processes needed to maintain port operability, (ii) variables related to a set of climate and oceanic-meteorological elements that could affect the former, and (iii) factors of resilience with the potential to moderate the impact of the selected climate and oceanic-meteorological elements (set of variables gathered in (ii)) on critical port processes (set of variables selected in (i)).

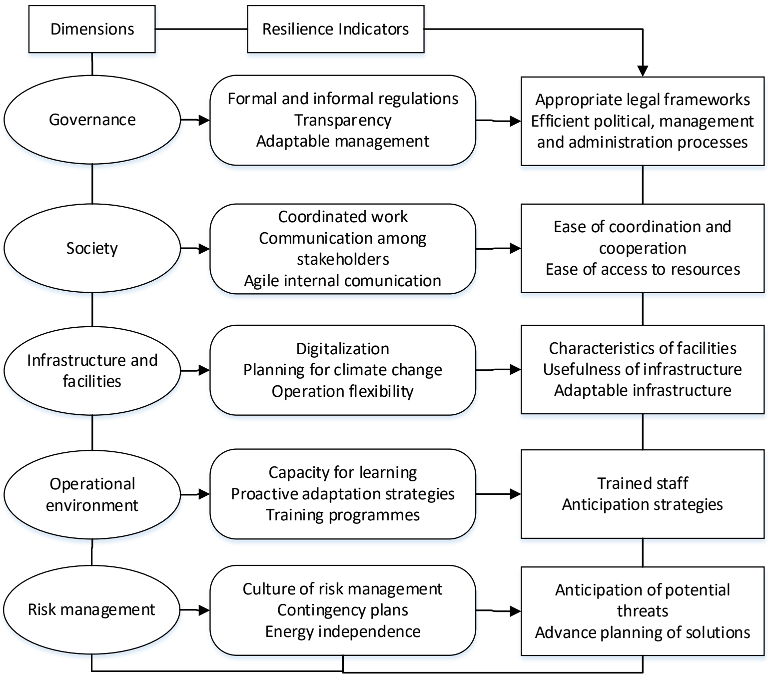
In parallel, inspired by the research of Summers et al. (2017), who drew up a measure of coastal community resilience to climate events, we established the dimensions that would make up our index of operational resilience (Figure 2). Although we used their same five dimensions (governance, society, infrastructure and facilities, operational environment, and risk management), the leap from “natural resilience” to “operational resilience,” as well as the move from “a coastal community” to “processes of a port,” required some small adaptations to reinforce those aspects that are really relevant in determining the operational resilience of port processes. Below, we explain in detail the adaptations carried out in two of the dimensions (society and natural environment) and their justification.

On the one hand, Summers et al. (2017) described the society dimension as all the cultural, nonstructural elements of the built environment, that is, “the objective and subjective relationships people can have with the material world and other people.” They address collaborative and communication relationships within coastal communities; our indicator does the same, but in our case, regarding the management of port operations. The adaptation carried out in this case was therefore minimal; it only affects the terminology to facilitate interactions and understanding by the different stakeholders.

On the other hand, Summers et al. (2017) defined the natural environment as a concept that “encompasses all living and nonliving things,” differentiating between “wild extensions (with no-human intervention)” and “managed lands.” As spaces with “no-human intervention” are exogenous to the management of operational resilience, our indicator only collects those questions (“management lands” in their terminology) related to human activity, that is, all those factors related to learning capacities, proactive adaptation strategies, and training programs to enhance the use individuals make of the port environment and, consequently, increase port operational resilience (Johnson et al., 2013, Chowdhury and Quaddas, 2017; Scholten et al., 2019).

Thus, following authors such as Johnson et al. (2013), Chowdhury and Quaddas (2017), or Scholten et al. (2019), we focused only on those sub-dimensions with an impact on operational resilience (i.e., learning and training), obviating those exclusively related to the resilience of the natural environment, with no effect on our index, as the port’s different experts (e.g., CETMAR, Meteogalicia) and stakeholders also corroborated. Pursuant to this refocusing toward the operational issues, we considered it more accurate to refer to this dimension as the “operational environment” rather than the “natural environment.” Figure 2 shows our conceptual framework for the dimensions of port resilience to the potential effects of climate change.

Figure 2. Conceptual framework for the dimensions of port resilience in relation to the effects of climate change. Adapted from Summers et al. (2017)



In the second stage, using the Delphi method, we established risk scenarios by crossing critical port processes (set of variables gathered in (i)) and climate and oceanic-meteorological phenomena (set of variables gathered in (ii)) to define the situations to which ports are most sensitive. Similarly, in the latter part of this stage, we crossed the risk scenarios obtained with the resilience factors selected in (iii) in a new Delphi session. The intention was to obtain an expert valuation of the moderating potential that these factors would have on the effects of a specific risk scenario in critical port processes.

Finally, in the last stage, we weighted the results of the second Delphi session using the average scores obtained in the first one for each of the risk scenarios, giving rise to five measures that represent the contribution made by each dimension of resilience to the increase in the adaptability of the port. Thus, after evaluating the port's resilience factors and adding them to our model, we obtained the targeted composite resilience index, that is, the adaptability of the port to the most important potential risks posed by climate change.

3.1 Delphi methodology and operational risk scenarios

To draw up the composite index, we used a Delphi technique in two rounds, which allowed for a rigorous approach to refining the list of indicators (Jordan and Javernick-Will 2013). Regarding the number of experts used, studies indicate that a minimum of seven and not more than 30 experts is optimal (Dalkey et al., 1970). Accordingly, following the final selection of possible variables of interest—port processes, climate phenomena, and resilience indicators—the first Delphi phase began with the initial matching between port processes and the climate and oceanic-meteorological phenomena identified. The comparison of these two types of elements was aimed at defining possible scenarios for operational risk and, in line with the scores that the experts granted, identifying scenarios involving the greatest potential threat for port processes due to exposure to adverse climate events resulting from climate change. A matrix of relations was drawn up between climate elements and port processes to classify a set of operational risk scenarios by the potential degree to which the former would affect the latter, both qualitatively and quantitatively.

For performing this first phase of the Delphi method, the experts were provided with information on the context of the project, the methodology to be used, and the rules governing the process. The matrix was then presented to the selected group, and they were requested to draw up their evaluations based on their expertise in three rounds. Scores from 0 to 3 were granted for the intersections according to the risk and in line with the scale shown in Figure 3.

Figure 3. Scale of risk levels

0 No risk	**1** Low risk	**2** Medium risk	**3** High risk

The participants answered the questionnaire anonymously, although after each session, they received aggregated information on the results to achieve greater convergence among the experts in the next Delphi round. In addition, for the internal analysis, descriptive statistics were measured—that is, the average, standard deviations, and variation coefficients for each of the possible resulting operational risk scenarios. This information, which was also shared with the participants, revealed the importance that the experts placed on the various risk scenarios (the average scores), as well as the degree of consensus achieved (standard deviations and variation coefficients). After a further review of the academic literature on parametric methods for processing the data obtained, we decided to adopt the criterion that Shah and Kalaian (2009) described. They proposed that the variation coefficient be used as a statistical tool for evaluating the degree of accordance between the opinions of the various participants in each round. We chose to select the various rounds of only those scenarios in which the variation coefficient was 0.50 or less. This choice was made to guarantee the maximum consensus on the selected scenarios.

Regarding the average value, Greatorex and Dexter (2000) suggested that in a Delphi method, this should be considered a valid measure for assessing the importance that the participants play in the various indicators because, as the measure of a central trend, the average score represents the panel's group opinion. In line with their paper, we established a second filter by selecting only those scenarios in which the average score was 2 or more—that is, the scenarios of operational risk on which the experts placed greater importance. The goal of this was to ensure the maximum consensus on the scenarios selected.

These scenarios of the greatest risk obtained in the first Delphi phase, together with the resilience factors selected at the start, were the inputs in the second Delphi phase. In view of the large quantity of data handled here, we decided to complete only two rounds in this second phase. The goal was to establish the degree to which the resilience factors identified might help to decrease the effects of the greater risk scenarios. We therefore drew up another matrix of relations containing, on the one hand, the greater risk scenarios and, on the other hand, the resilience factors grouped in each of the resilience dimensions. The comparison of these two aspects (risk scenarios vs. resilience factors) gives rise to what we call "impact moderation coefficients" (IMCs). An IMC allows us to obtain a quantitative measure of the contribution that each dimension of resilience makes to the increase in the adaptability of the port. This moderates the vulnerability of port processes to the impact of extreme weather events stemming from climate change (Sierra et al., 2017; McIntosh and Becker, 2019).

3.2. Normalization and calculation of impact moderation coefficients (IMCs)

The IMCs obtained were then weighted in light of the relative importance of each risk scenario (i.e., the results of the first Delphi). The average score of these weighted IMCs was calculated for each resilience factor (i.e., the matrix columns) to obtain the impact value of each resilience factor (a). See Table 1.

These values were grouped according to the resilience dimension to which they belonged and were added to obtain the value for each resilience dimension (b). Next, the impact values of each resilience factor (a) were divided by the value of each factor's respective resilience dimension (b) to obtain the weighed value for each resilience factor (c).

The average of these values (c) was then calculated, giving rise to the impact value of each resilience dimension (d). Subsequently, the impact values of the five resilience dimensions were added to obtain the resilience value (e). Finally, the impact values of each resilience dimension (a) were divided by the resilience value (b) to obtain the weighted value for each resilience dimension (c).

Table 1. Normalization and calculation of IMCs

	Dimension 1				…	Dimension n			
	Resilience factor1	*resilience factor2*	*Resilience factor 3*	*Resilience* factor 4	…	*Resilience* factor n_1	*Resilience* factor n_2	Resilience factor n_3	*Resilience* factor n_4
Weighted scenario 1	$\bar{X}CMI_{11}$	$\bar{X}CMI_{12}$	$\bar{X}CMI_{13}$	$\bar{X}CMI_{14}$	…	$\bar{X}CMI_{1n_1}$	$\bar{X}CMI_{1n_2}$	$\bar{X}CMI_{1n_3}$	$\bar{X}CMI_{1n_4}$
Weighted scenario 2	$\bar{X}CMI_{21}$	$\bar{X}CMI_{22}$	$\bar{X}CMI_{23}$	$\bar{X}CMI_{24}$	…	$\bar{X}CMI_{2n_1}$	$\bar{X}CMI_{2n_2}$	$\bar{X}CMI_{2n_3}$	$\bar{X}CMI_{2n_4}$
Weighted scenario 3	$\bar{X}CMI_{31}$	$\bar{X}CMI_{32}$	$\bar{X}CMI_{33}$	$\bar{X}CMI_{34}$	…	$\bar{X}CMI_{3n_1}$	$\bar{X}CMI_{3n_2}$	$\bar{X}CMI_{3n_3}$	$\bar{X}CMI_{3n_4}$
Weighted scenario 4	$\bar{X}CMI_{41}$	$\bar{X}CMI_{42}$	$\bar{X}CMI_{43}$	$\bar{X}CMI_{44}$	…	$\bar{X}CMI_{4n_1}$	$\bar{X}CMI_{4n_2}$	$\bar{X}CMI_{4n_3}$	$\bar{X}CMI_{4n_4}$
Weighted scenario 5	$\bar{X}CMI_{51}$	$\bar{X}CMI_{52}$	$\bar{X}CMI_{53}$	$\bar{X}CMI_{54}$	…	$\bar{X}CMI_{5n_1}$	$\bar{X}CMI_{5n_2}$	$\bar{X}CMI_{5n_3}$	$\bar{X}CMI_{5n_4}$
Weighted scenario 6	$\bar{X}CMI_{61}$	$\bar{X}CMI_{62}$	$\bar{X}CMI_{63}$	$\bar{X}CMI_{64}$	…	$\bar{X}CMI_{6n_1}$	$\bar{X}CMI_{6n_2}$	$\bar{X}CMI_{6n_3}$	$\bar{X}CMI_{6n_4}$
…	…	…	…	…	…	…	…	…	…
Weighted scenario n	$\bar{X}CMI_{n_1}$	$\bar{X}CMI_{n_2}$	$\bar{X}CMI_{n_3}$	$\bar{X}CMI_{n_4}$	…	$\bar{X}CMI_{nn_1}$	$\bar{X}CMI_{nn_2}$	$\bar{X}CMI_{nn_3}$	$\bar{X}CMI_{nn_4}$

(a) Mean	$\bar{X}_{FR1}$	$\bar{X}_{FR2}$	$\bar{X}_{FR3}$	$\bar{X}_{FR4}$	…	$\bar{X}FR_{n_1}$	$\bar{X}FR_{n_2}$	$\bar{X}FR_{n_3}$	$\bar{X}FR_{n_4}$
(b) Sum of dimensions	$S_1 = \sum \bar{X}_{FR1}..\bar{X}_{FR4}$				…	$S_n = \sum \bar{X}_{FRn_1}..\bar{X}_{FRn_4}$			
(c) Weighting of factors	$\bar{X}_{FR1}/S_1$	$\bar{X}_{FR2}/S_1$	$\bar{X}_{FR3}/S_1$	$\bar{X}_{FR4}/S_1$	…	$\bar{X}_{FRn_1}/S_n$	$\bar{X}_{FRn_2}/S_n$	$\bar{X}_{FRn_3}/S_n$	$\bar{X}_{FRn_4}/S_n$
(d) Average score of each dimension	$\bar{X}_{B1} = \bar{X}\,(\bar{X}_{FR1}.\bar{X}_{FR4})$				**…**	$\bar{X}_{Bn} = \bar{X}\,(\bar{X}FR_{n_1}..\bar{X}FR_{n_4})$			
(f) Weighting of dimensions	$P_1 = \bar{X}_{B1}/S_T$				**…**	$P_n = \bar{X}_{Bn}/S_T$			

(e) Sum of averages of dimensions
$S_T = \sum \bar{X}_{B1}..\bar{X}_{Bn}$

At the end of this weighting process, we drew up a self-assessment questionnaire and sent it to the port stakeholders so that they could judge the port's performance in relation to the IMCs identified. The ideal situation would be to send the questionnaire to all port stakeholders. In cases where it is not possible for all to participate, a stratified random sample with a proportional allocation that is representative of the total population of port stakeholders should be drawn. In both cases, it is necessary for the questionnaire responses received to respect the proportionality established in the initial sample. In addition, no statistically significant differences should exist between the selected subsamples. The scoring process followed a Likert 1-10 scale in which 1 meant "totally disagree" and 10 meant "totally disagree." Subsequently, their responses for each resilience factor were coded and the results added for the five dimensions of resilience.

After all these calculations, the PRI model was structured as shown in equation 1:

$$PRI = \beta_1 Dm_1 + \beta_2 Dm_2 + \beta_3 Dm_3 + \cdots + \beta_n Dm_n \qquad (\mathbf{1})$$

Where $\beta_1, \beta_2, \dots \beta_n$ = weights obtained after the normalization of the Delphi results.

$Dm_1, Dm_2, \dots, Dm_n =$ values that stakeholders granted to the dimensions of resilience in line with the self-assessment questionnaire.

It should be noted that our research responds to the assessment of port risk/resilience perceived according to stakeholders, taking advantage of and generating local knowledge. This inclusion of many viewpoints offers a holistic view of port resilience, with all stakeholders related to our research being represented. We could therefore identify both the various significant variables of our study and the interrelations among them. Our study was aimed at enhancing the analysis by including all agents related to port resilience as stakeholders in the research. This means we had to move away from most previous studies, which included only stakeholders directly related to the port infrastructure.

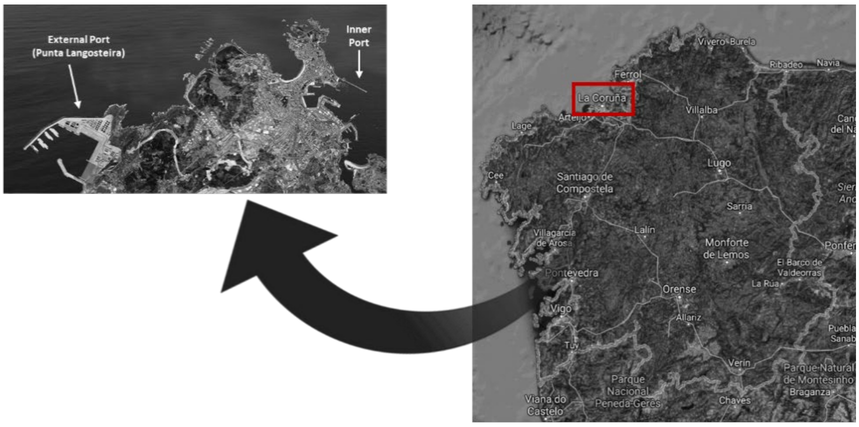
Note that the proposed index could be used from a resilience perspective, but it could also be adapted to the multilevel risk assessment approach that Izaguirre et al. (2020a) proposed, being framed at level 2 of this methodology.

4. RESULTS AND DISCUSSION: CALCULATING THE PRI IN A CASE STUDY

4.1. Explanation of the case study: the external port in A Coruña (Spain)

The port of A Coruña is located where the Atlantic Ocean meets the Cantabrian Sea (Figure 4). The infrastructure of the external port in A Coruña was chosen as the case study for our research because its characteristics made it appropriate for our research questions. Not only does it feature a full collection of climate and oceanic-meteorological data, but it also possesses certain unique characteristics that are critical for the study of climate change effects:

Figure 4. Location of the external port in A Coruña



a) Firstly, it is a nodal point included in the main network of the Trans-European Transport Network (TEN-T)[1]. This means it forms part of the main European transport arteries which carry the main flows for European supply chains.

b) It is an external port in which conditions are inherently adverse and has no natural protection against oceanic and meteorological effects. In fact, temperature variation in this port is 13°C, and average wave height is 6 meters, reaching maxima of 15-16 meters (Ministerio para la Transición Ecológica, 2019).

c) It is located on the western coast of Europe which, according to European Union predictions, will be a critical point for climate change: this region faces not only a greater risk of flooding because of rising sea levels but also a possible increase in storm surges (European Environmental Agency, 2017).

d) The infrastructure is new (2012) and has an estimated useful life of 50 years (Puertos del Estado, 2012), so in principle there is a high probability that it will face potential adverse effects of climate change.

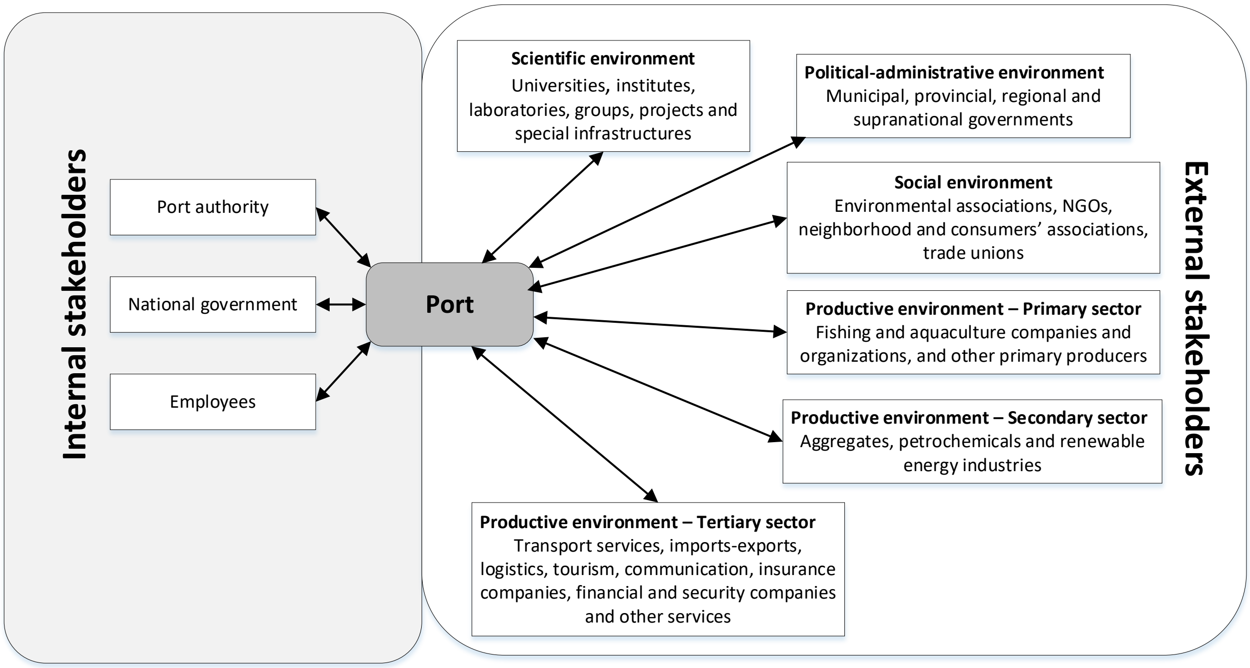
All these factors provide an ideal testing ground for the possible effects of climate change. Whether the external port in A Coruña will reach the status of a "talking pig" (Siggelkow, 2007), unlike other ports, it clearly had the features we needed for our research.

[1] According to the European Commission (2020), the Trans-European Transport Networks is a planned set of top-priority transport networks devised to facilitate transport for people and goods throughout the European Union.

4.2. Application of the methodology to the calculation of the PRI

In line with the methodology described above, the first task for applying it to the external port in A Coruña was to identify the stakeholders as shown in Figure 5 (see the full list in Annex 1).

Figure 5. Structure of stakeholders in port infrastructure



Next, together with experts from Meteogalicia (Galician meteorological service), the Centro Tecnológico del Mar – Fundación CETMAR (Technological Center of the Sea – CETMAR Foundation), and the Port Authority of A Coruña, we identified the climatic and ocean-meteorological elements with the greatest potential for causing operational disruptions at the external port of A Coruña. Based on empirical studies (Serrano-Notivoli et al., 2017; Vousdoukas et al., 2017; Santos et al., 2018) and official databases (Meteogalicia, 2015, 2016; AEMET, 2018; Puerto de A Coruña, 2018), we established a baseline for 2018 and a series of projections for 2050 according to a Representative Concentration Pathway (RCP) 8.5 (pessimistic) scenario. A detailed description of the sources used in this stage is contained in Annex 2.

The last step was to identify those port processes that, being pivotal for the continuity of the port's operations, the selected climate-related events could most affect (Annex 2). This selection was built upon the process master of the external port of A Coruña and, again, was carried out under the advice of Meteogalicia and the CETMAR. Finally, the resilience factors were grouped according to their corresponding dimensions (Annex 3). Once the basic information was gathered and structured, we carried out the Delphi methodology.

4.2.1. Delphi methodology and operational risk scenarios

The three rounds of the first Delphi phase were carried out between 12 February and 6 March 2019. We then selected a group of 22 experts to participate in the Delphi sessions, following advice from the A Coruña Port Authority and the CETMAR. An invitation was sent by email to the experts identified, together with general information and a link to a digital platform, where they could access the online questionnaire. In each of the rounds, one week after the request, reminders were sent by email.

The experts were requested to carry out an evaluation based on their expertise, matching selected port processes in the external port of A Coruña with oceanic-meteorological elements, according to a 0-3 Likert scale (Figure 3). The details of the experts who participated in all of the Delphi rounds are given in Annexes 4 and 5. Of the 22 experts contacted, 16 completed all three rounds, resulting in a participation rate of 73.72%.

The participants answered the questionnaire anonymously. After each of the sessions, they were provided with aggregated information on the results so that they could converge as far as possible in their scores during the next round. As a result of the methodological restrictions relative to the coefficient of variation and the average, we ended up with a set of 13 medium- and high-risk scenarios (Table 2).

We see, for example, that experts gave an average score of 2.25 to the potential impact of *23-24 days a year when wave height is significantly higher than 6 meters* on the processes of the *entry and exit of ships*. As the average score is greater than 2 and the variation coefficient is less than 0.50, this risk scenario was chosen for the next phase.

Table 2. Risk scenario scoring matrix by crossing critical port activities (columns) with climate and oceanic-meteorological factors (rows) (1st Delphi results)

CLIMATE AND OCEANIC-METEOROLOGICAL FACTORS	Port traffic control	Emergencies	Environmental control	Port police	General cleaning	Ship entry and exit	Ship stay	Unloading	Loading	Transport and storage	Movement of goods on land	Passenger embarkation/ desembarkation
23-24 days a year when wave height is significantly higher than 6 meters	1,81	1,75	1,06	1,13	0,88	2,25[a]	2,00[b]	2,00[c]	2,06[d]	1,00	0,44	1,19
0,2 to 0,4 meter increase in sea level	0,75	0,81	0,56	0,75	0,56	0,81	1,25	1,25	1,25	0,69	0,38	0,69
31-54 days a year when temperature is above 25ºC	0,31	0,88	1,13	0,56	0,69	0,31	0,44	0,69	0,75	1,13	0,44	0,81
23-30 days a year when average temperature is below 8,8ºC	0,44	0,63	0,75	0,56	0,56	0,31	0,44	0,50	0,56	0,63	0,44	0,69
35-55 days a year when average sustained wind speed is above 45 Km/h	1,69	1,63	1,38	1,06	1,56	2,13[e]	1,88	2,13[f]	2,19[g]	1,31	1,19	1,63
6-10 days a year when rainfail is above 30 litres/m^2	1,19	1,19	1,19	1,06	1,13	1,06	1,00	2,00[h]	2,00[i]	1,56	1,44	1,44
37-40 days a year with fog	2,06[j]	1,56	0,75	1,25	0,81	2,13[k]	1,06	1,38	1,44	0,88	1,38	1,25
About 2 days a year when sea roughness inside the port is above 0,55 meters and peak wave is above 17 seconds	1,50	1,19	0,56	0,75	0,63	1,88	2,06[l]	2,06[m]	1,94	0,69	0,56	1,19

In line with these results, the following risk scenarios were selected for the next phase:

- Impact of wave height on ship entry/exit [a]
- Impact of wave height by overrun on ship stay [b]
- Impact of wave height on unloading [c]
- Impact of wave height on loading [d]
- Impact of wind on ship entry/exit [e]
- Impact of wind on unloading [f]
- Impact of wind on loading [g]
- Impact of rain on unloading [h]
- Impact of rain on loading [i]
- Impact of fog on traffic control / operations [j]
- Impact of fog on ship entry / exit [k]
- Impact of wave roughness (wave height inside the port and wave period on ship stay [l]
- Impact of wave roughness (wave height inside the port and wave period) on unloading [m]

As can be seen in Table 2, certain risk scenarios can seriously compromise the port's operation. In fact, the highest-risk scenario for operational resilience takes place, in the opinion of the experts, when the increase in the height of the waves (climate factor) and the processes of the entry/exit of vessels intersect (score of 2.25). It seems evident that an increase in the height of the waves would compromise the entry/exit of ships and therefore the operational functioning of the port facilities. This score is consistent with various authors. Rusu and Soares (2013) and Santos et al. (2010), among others, established that activities in the harbor areas are strongly dependent on the wave conditions; the entrance and exit of ships even in safe conditions may cause them to sink.

Similarly, those scenarios related to wind speeds greater than 45 km/h, as well as the stowage (score 2.19) and ship unloading (score 2.13), can significantly compromise the operational resilience. We must bear in mind that cranes have a wind speed threshold above which they are legally obliged to stop their operations (McEvoy et al., 2013). Therefore, loading and unloading operations are expected to slow down as the wind speed increases and may even stop this work area, thus affecting the entire port's operational resilience.

As the risk scenarios have been identified in Table 2, we can now move on to the next stage: the second phase of the Delphi analysis, where the experts score the moderating effect that different resilience factors may have on risk scenarios. This allowed us to identify those key resilience factors on which to act to ensure the port's operational resilience. This phase was carried out from 23 March to 10 April 2019. Taking the scenarios calculated in the first Delphi phase, as well as the resilience factors selected for the external port of A Coruña, we drew up a new relationship matrix. This matrix was presented to the initial 22 experts, of whom 19 completed the two rounds (a participation rate of 86.36%). The result of this second Delphi stage is a matrix of average scores that the experts provided for the IMCs (Annex 6). Several examples are attached below to help with interpreting these relationships.

Following the previous example, we see that the experts now gave an average score of 1.89 (See Annex 6) to the moderating effect that resilience factor 4 (*Use of adaptive management principles for dealing* *with uncertainty*), included in the governance dimension, has on the risk scenario of the *impact of wave height on ship entry/exit*.

4.2.2. Normalization and calculation of the impact moderation coefficients (IMCs)

The average scores for the IMCs obtained in the second Delphi phase were multiplied by the average scores that the experts gave to the risk scenarios they comprised. This made it possible to weigh the average scores in terms of the importance that the experts placed on each of the scenarios. Table 3 shows the data obtained for these weightings.

In our example, the IMC of 1.89—obtained in the second Delphi—was weighted according to the score for the risk scenario (2.25)—the first Delphi—to obtain a weighted IMC of 4.26. Together with the weighted IMC of the other four resilience factors in this group, we calculated—as detailed in the methodology—the weight of the *governance dimension* in the resilience index.

Table 3. Normalization and calculation of the IMCs

	GOVERNANCE				SOCIETY				INFRASTRUCTURE AND FACILITIES				OPERATIONAL ENVIRONMENT				RISK MANAGEMENT			
Risk scenarios	R.F.1	R.F.2	R.F.3	R.F.4	R.F.5	R.F.6	R.F.7	R.F.8	R.F.9	R.F.10	R.F.11	R.F.12	R.F.13	R.F.14	R.F.15	R.F.16	R.F.17	R.F.18	R.F.19	R.F.20
Impact of wave height on ship entry/exit	3,55	2,84	3,43	4,26	2,84	4,26	4,26	2,37	4,26	4,03	2,72	4,03	4,74	4,50	2,96	2,61	4,38	3,67	3,20	2,37
Impact of wave height by overrun on ship stay	3,47	2,55	3,06	3,57	2,65	3,98	3,67	2,04	3,98	3,26	2,35	4,08	3,98	3,77	2,65	2,24	4,08	3,37	2,86	1,94
Impact of wave height on unloading	3,11	2,22	2,75	3,29	2,31	3,38	3,46	1,87	3,20	2,84	2,58	3,82	3,55	3,29	2,58	2,04	3,46	2,93	2,58	2,13
Impact of wave height on loading	3,22	2,39	2,95	3,41	2,39	3,50	3,59	1,84	3,32	3,04	2,86	3,87	3,68	3,32	2,58	2,12	3,68	3,04	2,58	2,21
Impact of wind on ship entry/exit	3,53	2,68	3,77	4,38	3,29	4,99	4,38	2,31	4,14	4,14	3,04	4,26	4,63	4,63	3,53	2,68	4,87	3,89	3,65	2,56
Impact of wind on unloading	4,11	3,08	4,11	4,62	3,34	5,13	4,88	2,69	4,75	4,62	3,98	5,26	5,13	5,00	3,98	2,95	5,26	4,36	3,85	2,95
Impact of wind on loading	4,11	3,21	4,11	4,49	3,21	5,13	4,88	2,57	5,00	4,62	3,85	5,26	5,13	5,00	4,11	2,95	5,39	4,36	3,85	2,95
Impact of rain on unloading	2,67	2,10	2,48	3,15	2,19	3,15	3,43	1,91	3,15	3,05	2,67	3,72	3,43	3,43	2,58	2,19	3,72	2,86	2,67	1,91
Impact of rain on loading	2,67	2,00	2,48	3,15	2,19	3,15	3,43	1,91	3,05	2,96	2,67	3,63	3,43	3,43	2,58	2,19	3,72	2,86	2,67	2,10
Impact of fog on traffic control/operations	3,69	2,39	3,15	3,80	2,61	4,23	3,91	2,17	3,80	3,58	2,61	3,91	3,80	4,02	2,82	2,50	4,34	3,15	3,04	2,17
Impact of fog on ship entry/exit	3,47	2,45	3,37	3,77	2,65	4,08	3,57	2,14	3,57	3,26	2,55	3,57	3,57	3,77	2,65	2,35	4,08	3,16	2,86	2,04
Impact of roughness on ship stay	3,36	2,57	3,06	3,55	2,66	3,95	3,55	2,07	3,85	3,36	2,57	4,14	3,85	3,75	2,57	2,27	3,65	3,06	2,66	1,97
Impact of roughness on unloading	3,47	2,63	3,16	3,68	2,53	4,11	3,68	2,32	4,21	3,58	2,84	4,42	4,11	4,00	2,84	2,42	3,89	3,37	2,95	2,11
Mean	3,42	2,55	3,22	3,78	2,68	4,08	3,90	2,17	3,87	3,56	2,87	4,15	4,08	3,99	2,95	2,42	4,19	3,39	3,03	2,26
Sum of dimensions	12,96				12,83				14,45				13,45				12,88			
Weighting of factors	0,264	0,2	0,25	0,29	0,21	0,32	0,3	0,17	0,27	0,25	0,2	0,29	0,3	0,3	0,22	0,18	0,33	0,26	0,24	0,18

Average score of each dimension	3,24	3,21	3,61	3,36	3,22
Weighting of dimensions	0,1947	0,1927	0,2170	0,2021	0,1935

Sum of averages of dimensions	16,64

We then drew up a questionnaire for stakeholder self-assessment in the A Coruña external port. Table 4 shows, on the one hand, the number of stakeholders who make up the population of the port, as well as the percentage they represent of the total. On the other hand, the response percentages obtained for each subsample are detailed considering that an invitation was sent by email to the total population. A Kruskal-Wallis test helped us to ensure that no statistically significant differences existed between the various subsamples. Based on a 1-10 Likert scale, participants were asked to evaluate the port's current situation in the five resilience dimensions selected.

Table 4. Response rate to the resilience assessment questionnaire by stakeholders (grouped by category) in the external port of A Coruña

	Secondary sector	**Tertiary sector**	**Social environment**	**Political administrative environment**	**Scientic environment**	**Total**
Total Stakeholders (number/%)	4 (6,6%)	36 (59,0%)	4 (6,6%)	12 (19,6%)	5 (8,2%)	61 (100%)
Emails sended	4	36	4	12	5	61
Answers received (number/%)	4 (7,0%)*	33 (57,9%)*	4 (7,0%)*	11 (19,3%)*	5 (8,8%)*	57 (100%)*

** No significant difference between distribution of stakeholders and the study sample*

Note: Although the list of stakeholders of the Port of A Coruña includes the primary sector, it has not been included in the study. This port is formed by two locations: the external port and the internal, and our study was carried out in the first one (with a greater impact from climate change) while the fishing activities correspond entirely to the second one.

The results obtained from calculating the IMCs and coding the responses to the questionnaire are given in Table 5:

Table 5. Estimated results and coding of the stakeholder questionnaire

	Weighting	**Current state** [(1)]
Governance	19,50%	65,06%
Society	19,30%	61,94%
Infrastructure and facilities	21,70%	48,15%
Operational environment	20,20%	47,47%
Risk management	19,30%	36,95%

[(1)] Based on potential 100% maximun performance for each of the dimensions. The values are the result of coding of the port stakeholders questionnaire (available on request).

With this information, we then established the PRI for the A Coruña external port. Based on equation 1 described in the methodology, the result is as follows:

$$\boldsymbol{IRP = 19,5 * 65,06\% + 19,3 * 61,94\% + 21,7 * 48,15\% + 20,2 * 47,47\% + 19,3 * 36,95\% = 51,80\%}$$

The results show that the A Coruña external port has a level of resilience of 51.8% and that the dimensions related to infrastructure and facilities (48.1%) or the learning and risk-management procedures (47.5% and 37.0%, respectively) are especially sensitive.

Although the ideal situation would be a PRI = 100%, this does not seem to be feasible because the cost required to reach this threshold would not justify the improvements obtained. We estimate that, as with other indices of a similar nature, a performance of around 80% would be a reasonable objective. In accordance with this, it is concluded that the PRI of the port of A Coruña is up to 28 percentage points below the desirable optimum situation—that is, with a level of compliance of 65% with respect to the optimal situation.

Beyond this global result, the PRI allows us to analyze the relative importance of the various dimensions, as well as their contribution to the global PRI. In accordance with this, we observe that the dimensions with the greatest capacity for improvement in protection against climate change are, in this order, risk management, staff education and training, and infrastructure and equipment. Based on these results, it seems reasonable to adopt a series of measures that, without requiring high costs, could contribute very positively to raising each of these dimensions to achieve the target PRI of 80%. For example, the implementation of training programs on climate change—within training plans administered to port staff—or the implementation of a technological surveillance system that allows for identifying best practices in port adaptation to climate change, among others, could greatly contribute to reinforcing these weaker dimensions. Similarly, the digitization of the collection and the transmission of information throughout the supply chain, as well as that of emergency plans, would favor the monitoring of the various KPIs that may affect operational continuity, as well as the establishment of more efficient programs for continuous improvement.

5. CONCLUSIONS

The port infrastructure is of vital importance in global supply chains. The analysis of port resilience is therefore key to trying to maintain or restore their operability as quickly as possible in light of the extreme effects of climate change, which we either see today or can expect to see increasingly in coming years. It is important not only to determine the adaptability of ports, but also, and above all, to identify the factors on which work needs to be done to increase their resilience.

However, we have found that the tools existing today for measuring port resilience are limited, use a partial focus, or do not include all stakeholders involved. Conversely, our research has led to the development of an evaluation tool for measuring and classifying the level of resilience of an external port to the potential effects of climate change, taking into account every port stakeholder, and following a quantitative approach. The methodology proposed also allows us to weigh each dimension of resilience in terms of the answers that the stakeholders gave (both internal and external). The PRI enables the various agents related to the port and its environment to obtain valuable information on which to base their decisions because it offers a triple view: (i) the total resilience of the port, (ii) the importance of each dimension for improving port adaptability, and (iii) the current performance of port processes in relation to resilience to climate change.

From an academic point of view, this research helps with mitigating the shortage of port indicators that authors such as Shakou et al. (2019) and Laxe et al. (2017) mentioned. Additionally, the inclusion of all stakeholders in the drafting of the index reduces the bias that is usually found in indicators based on the vision of just some of them (Bryson, 2004; Few et al., 2007). In addition to the academic contributions, the use of simple, easy-to-interpret indicators facilitates their dissemination in society. Furthermore, the study offers important contributions to port managers, supply chains, and policy makers. Regarding the management of ports and value chains, the fact that stakeholders are involved in the development of the resilience index seems to be a measure that will encourage greater participation by everyone involved in improving resilience. The index provides them with a tool with which to quantify their improvement processes in this area. It will also facilitate informed decisions by policy makers in the medium and long terms in the fight against climate change. The weighting of the factors and dimensions of resilience provides them with a tool for maximizing the efficient use of resources, focusing on the factors that will have the greatest impact on resilience. This is especially important bearing in mind that investment by ports in disaster prevention tends to be limited because it is enormously complex (Xiao et al., 2015).

Another possible line of research would be to scale the index to a multi-port model following the methodology proposed here. This would allow for comparisons among various ports.

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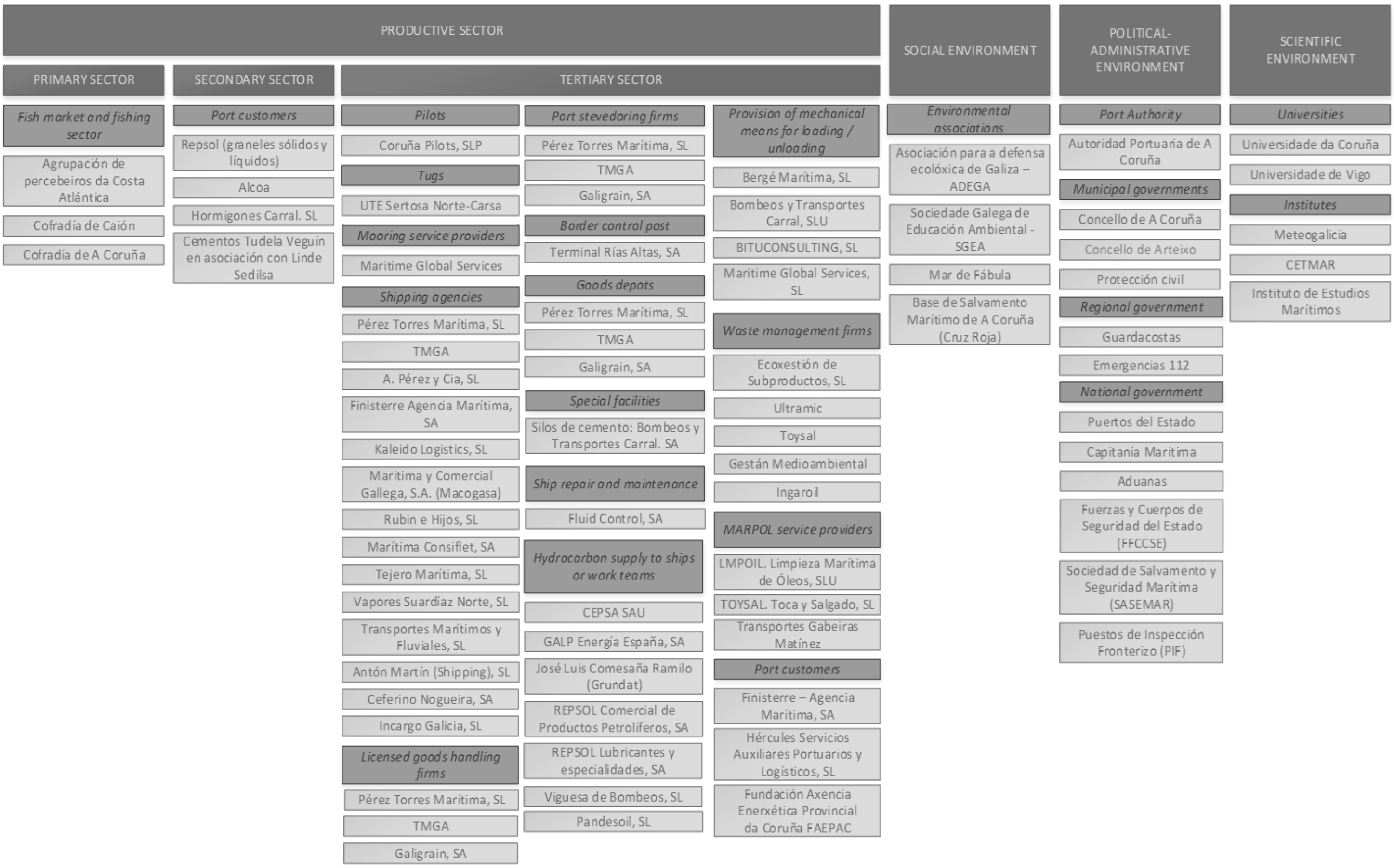
7. ANNEXES

Annex 1. Stakeholders identified in the facilities at the A Coruña external port



Annex 2. Climatic and ocean-meteorological elements, as well as port process selected for the Port of A Coruña

By 2050, between 23 and 24 days a year with waves significantly higher than 6 meters (value in 2018: 27 days)[1]
By 2050, an increase of between 0.2 and 0.4 meters in sea level (shelter on the inner pier in 2018: 2 meters; shelter on the main levee in front of the overflow: 20.5 meters)[2]
By 2050, between 31 and 54 days a year with a temperature above 25° C (value in 2018: 14 days)
By 2050, between 23 and 30 days a year with an average temperature below 8.8° C (value in 2018: 18 days)
By 2050, between 35 and 55 days a year with average sustained wind greater than 45 km / h (2018 value: 24 days)
By 2050, between 6 and 10 days with rains above 30 l/m2 (value in 2018: 7 days)
By 2050, between 37 and 40 days per year with fog (value in 2018: 37 days)[3]
By 2050, around 2 days a year with agitation inside the port greater than 0.55 meters[4] and a peak period of the wave at the buoy greater than 17.0 seconds (value in 2018: 2 days)

Notes:

[1] Affection by overflow events to the main dam service area and access to future pontoons perpendicular to it.

[2] Current shelter of the inner dock and the main dock with respect to the situation of maximum high tide alive equinoctial (HTAE +4.5 m): 2.0 meters and 20.5 meters, respectively (shelter: difference between the crowning height of the dock and the dike with respect to the sea at high tide alive equinoctial).

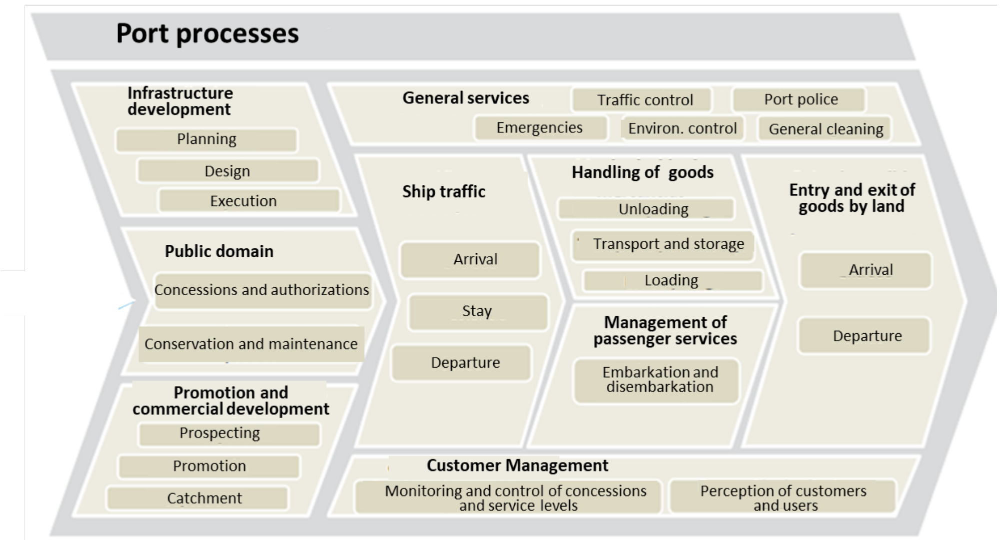
[3] Fog is considered when visibility is less than 1 kilometer away.

[4] Estimate made based on a significant wave height of 6 meters outside of the port.

The established reference thresholds are those from which it is considered that a certain incidence exists for the operation of the port. The data are based on a RCP 8.5 (pessimistic scenario) for the period of 2031-2060 in the area of the case study.

Port Process

Figure 6. Port process master of A Coruña



Starting from the process master of the outer port of A Coruña (Figure 6), and with the advice of the experts from Meteogalicia (Galician meteorological service), the CETMAR, and the Port Authority of A Coruña, we proceeded to identify those processes with greater exposure to the effects of extreme climatic and oceanic-meteorological events, as well as those that, in turn, play a key role in the continuity of the port's operations. The selected processes are detailed below:

- Port traffic and control
- Emergencies
- Environmental control
- Port police
- General cleaning
- Ship entry and exit
- Ship stay
- Unloading
- Loading
- Transport and storage
- Movement of goods on land
- Passenger embarkation/disembarkation

Annex 3. Composition of dimensions of resilience

GOVERNANCE	Existence of policies institutionalizing resilience as a target
	Institutional transparency and participation by public and private stakeholders in decision-making
	Clarity and respect for formal and informal regulations, with regular updating of elements of legal compliance (regulations)
	Use of adaptive management principles to deal with uncertainity (iterative decision-making, inclusion of feedback and testing / updating of assumptions
SOCIETY	Comunication amomg stakeholders
	Fast internal comunication protocols in the Port Authority
	Coordinated work with Administrations and suppliers of supply chain logistics infrastructure to plan connected, resilient logistics centers
	Facility for reaching agreements with other nearby ports
INFRASTRUCTURE AND FACILITIES	Planning of operational continuity for infrastructure and facilities in case of climate change effects
	Digitalization: existence of unfiled technology to facilitate information flows throughout the supply chain
	Existence of systems to improve transport flexibility and avaliability
	New infrastructure / facilities and sustainability and adaptability of existing ones
OPERATIONAL ENVIRONMENT	Capacity to learn from and anticipate climate change impacts
	Existence of long-term proactive strategies to adapt to climate change
	Climate change training programs, forming part of human capital training
	Fair adaption measures: the effects and costs of the different efforts at adaptation should considered in the varios groups / sectors
RISK MANAGEMENT	Risk management tools
	Culture of risk management throughout the supply chain
	Collaboration with insurance providers to determine the quantitative elements of climate risk in order to properly insure risks that can not be reduced
	Generation of renewable energy in the port to avoid risks associated with power outages

Note: The resilience factors were selected through the literature review (see, e.g., Becker et al., 2018; McEvoy and Mullett, 2013). These factors were selected because we believed that they were valid to apply to any type of port. Subsequently, they were grouped in the five dimensions detailed in the Section 3.

Annex 4. List of experts who participated in the first Delphi round

Expert	Field of expertise	Organization represented
Expert 1	Port processes	Galigrain (firm)
Expert 2	Port processes	Maritime Safety Coordinator (Sea captaincy)
Expert 3	Port processes	Technology center of the sea
Expert 4	Resilience	University of A Coruña (UDC)
Expert 5	Port processes	Repsol YPF (firm)
Expert 6	Resilience	GII (Integrated Engineering Reserach Group) –UDC
Expert 7	Port processes	TMGA (logistic firm)
Expert 8	Port processes	University of A Coruña (UDC)
Expert 9	Climate change	Meteogalicia - (Meteorological agency of Galician government)
Expert 10	Climate change	University of Vigo (Uvigo)
Expert 11	Resilience	Port authority of A Coruña
Expert 12	Climate change	University of Vigo (Uvigo)
Expert 13	Resilience	University of A Coruña (UDC)
Expert 14	Port processes	Pérez Torres Marítima, S.L (firm).
Expert 15	Resilience	Hydrographic Institute of Portugal
Expert 16	Port processes	Port authority of A Coruña

Annex 5. List of experts who participated in the second Delphi round

Expert	Field of expertise	Organization represented
Expert 1	Port processes	Galigrain (firm)
Expert 2	Port processes	Maritime Safety Coordinator (Sea captaincy)
Expert 3	Port processes	Technology center of the sea
Expert 4	Resilience	University of A Coruña (UDC)
Expert 5	Port processes	Repsol YPF (firm)
Expert 6	Resilience	GII (Integrated Engineering Reserach Group) –UDC
Expert 7	Climate change	Hydrographic Institute of Portugal
Expert 8	Port processes	TMGA (logistic firm)
Expert 9	Port processes	University of A Coruña (UDC)
Expert 10	Resilience	Aquática Ingeniería Civil (firm)
Expert 11	Climate change	Meteogalicia - (Meteorological agency of Galician government)
Expert 12	Climate change	University of Vigo (Uvigo)
Expert 13	Resilience	Port authority of A Coruña
Expert 14	Climate change	University of Vigo (Uvigo)
Expert 15	Resilience	University of A Coruña (UDC)
Expert 16	Port processes	Pérez Torres Marítima, S.L (firm).
Expert 17	Resilience	Hydrographic Institute of Portugal
Expert 18	Port processes	Port authority of A Coruña
Expert 19	Port processes	Acadar/McValnera (firm)

Annex 6. Resilience factor scores that experts gave to various risk scenarios (2nd Delphi results)

	GOVERNANCE				COLLABORATION AND COMUNICATION				INFRAESTRUCTURE AND FACILITIES				LEARNING AND TRAINING				RISK MANAGEMENT			
Risk scenarios	R.F.1	R.F.2	R.F.3	R.F.4	R.F.5	R.F.6	R.F.7	R.F.8	R.F.9	R.F.10	R.F.11	R.F.12	R.F.13	R.F.14	R.F.15	R.F.16	R.F.17	R.F.18	R.F.19	R.F.20
Impact of wave height on ship entry/exit	1,58	1,26	1,53	1,89	1,26	1,89	1,89	1,05	1,89	1,79	1,21	1,79	2,11	2,00	1,32	1,16	1,95	1,63	1,42	1,05
Impact of wave height by overrun on ship stay	1,79	1,32	1,58	1,84	1,37	2,05	1,89	1,05	2,05	1,68	1,21	2,11	2,05	1,95	1,37	1,16	2,11	1,74	1,47	1,00
Impact of wave height on unloading	1,84	1,32	1,63	1,95	1,37	2,00	2,05	1,11	1,89	1,68	1,53	2,26	2,11	1,95	1,53	1,21	2,05	1,74	1,53	1,26
Impact of wave height on loading	1,84	1,37	1,68	1,95	1,37	2,00	2,05	1,05	1,89	1,74	1,63	2,21	2,11	1,89	1,47	1,21	2,11	1,74	1,47	1,26
Impact of wind on ship entry/exit	1,53	1,16	1,63	1,89	1,42	2,16	1,89	1,00	1,79	1,79	1,32	1,84	2,00	2,00	1,53	1,16	2,11	1,68	1,58	1,11
Impact of wind on unloading	1,68	1,26	1,68	1,89	1,37	2,11	2,00	1,11	1,95	1,89	1,63	2,16	2,11	2,05	1,63	1,21	2,16	1,79	1,58	1,21
Impact of wind on loading	1,68	1,32	1,68	1,84	1,32	2,11	2,00	1,05	2,05	1,89	1,58	2,16	2,11	2,05	1,68	1,21	2,21	1,79	1,58	1,21
Impact of rain on unloading	1,47	1,16	1,37	1,74	1,21	1,74	1,89	1,05	1,74	1,68	1,47	2,05	1,89	1,89	1,42	1,21	2,05	1,58	1,47	1,05
Impact of rain on loading	1,47	1,11	1,37	1,74	1,21	1,74	1,89	1,05	1,68	1,63	1,47	2,00	1,89	1,89	1,42	1,21	2,05	1,58	1,47	1,16
Impact of fog on traffic control/operations	1,79	1,16	1,53	1,84	1,26	2,05	1,89	1,05	1,84	1,74	1,26	1,89	1,84	1,95	1,37	1,21	2,11	1,53	1,47	1,05
Impact of fog on ship entry/exit	1,79	1,26	1,74	1,95	1,37	2,11	1,84	1,11	1,84	1,68	1,32	1,84	1,84	1,95	1,37	1,21	2,11	1,63	1,47	1,05
Impact of roughness on ship stay	1,79	1,37	1,63	1,89	1,42	2,11	1,89	1,11	2,05	1,79	1,37	2,21	2,05	2,00	1,37	1,21	1,95	1,63	1,42	1,05
Impact of roughness on unloading	1,74	1,32	1,58	1,84	1,26	2,05	1,84	1,16	2,11	1,79	1,42	2,21	2,05	2,00	1,42	1,21	1,92	1,68	1,47	1,05

This matrix allows us to identify those key resilience factors on which to act to ensure the operational resilience of the port for each risk scenario. Several examples are included below to help to interpret these relationships.

Example 1. *To increase the operational resilience of the port against, for example, the first risk scenario of "impact of wave height on ship entry/exit," the most appropriate thing would be to focus mainly on two resilience factors (RFs). These include RF13 ("Capacity to learn from and anticipate climate change impacts") and RF14 ("Existence of long-term proactive strategies to adapt to climate change"), which have the highest scores (2.11 and 2.00, respectively).*

- Regarding RF13, the proper training of port operators on the potential effects of wave height in the entry/exit processes of ships and how to reduce them will result in greater operational resilience. As various authors have argued, generating and disseminating this type of knowledge among stakeholders allows for the establishment of new routines with which to face non-routine situations (e.g., Johnson et al., 2013; Chowdhury and Quaddas, 2017; Scholten et al., 2019).

- Regarding RF14, the design of proactive strategies for facing the potential effects of wave height on the processes of the entry/exit of vessels will allow for increasing the shielding of the port in the face of this risk scenario. Research shows that proactive adaptation designed to reduce vulnerabilities is far more cost effective than mitigation or reactive strategies are (Pielke, 2007; Becker et al., 2012).

***Example 2**. RF8 ("Facility for reaching agreements with other nearby ports") and RF20 ("Generation of renewable energy in the port to avoid risks associated with power outages") would be the last initiatives to act on, as they present the lowest scores (1.05) (i.e., their influence in operational resilience is minimal in the opinion of experts).*