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A new approach to assessing port infrastructure resilience to climate risks and adaptive solutions prioritization

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ABSTRACT

Globalisation, cost and technological competitiveness, public climate awareness and quick sharing of information may justify strong tendencies for quick-fix ?copy-and-paste? solutions for survival to climate challenges faced by ports. However, owing to the particularity, role, trade-off challenges, and uniqueness of each port, this approach is bound to fail.
A modern resilient port requires a unique forward-looking management approach to climate change based on port logistic resilience rather than just infrastructural resilience. Embedded in ?divide and conquer? problem-solving strategy, the proposed methodology in this paper is a useful solution-focussed approach that serves to disintegrate climate change complexities into simplistic scenarios; thereby ensuring that each port contextualises its own climate problem and translate it into solvable entities. Adaptive solutions for low resilience score scenarios may then be assessed based on existing known methods (Costs benefit analysis, Multi-criteria analysis and Cost efficiency analysis, Source-Pathway-Receptor etc.).

1. Introduction

In recent decades, focussing on logistic chain has proved to be a way of reducing the price of goods (PIANC, 2014) and therefore gaining competitive advantage. An efficient logistic chain can effectively contribute to lower final cost of product either by reducing transport costs or inventory costs or both. Logistic chains have nowadays become the main drivers for trade (Liu & Lam, 2015). Ports, as essential players in the logistic chains, are increasingly expected to fulfil seamless logistic chain requirements (Gaur, 2006). This is heightened by the fact that global trade is largely seaborne (91%); with cargo ships carrying approximately 50 000 billion tonne-miles (UNFCCC, 2013) moving through ports to reach consumers. Seaport efficiency has been widely recognised as a major determinant of maritime transport costs (Loh & Thai, 2015; Dollar, Clark, & Micco, 2002). As a result, the development of maritime transportation infrastructure is increasingly becoming a key enabler and catalyst for the competitiveness and development of any regional economy, especially due to the large positive externalities often generated by port activities (Liu & Lam, 2015). Poor infrastructure is believed to account for more than 40% of transport costs (Dollar, Clark, & Micco, 2002). As distances are shortened by globalisation, the economies of the world become more interdependent and the role of ports is gradually shifting from a set of complex infrastructures to a major player in national logistic chain management which majority of the population heavily rely on for day to day necessities and employment. Given the current high population growth rate, this trend is likely to continue and further increase in future, thereby gradually strengthening the positive correlation between logistic chain services and human survival. In spite of this development, climate change has however brought serious threats to the port logistic chain and this is mainly due to the fact that seaports are located on coasts that are susceptible to climate variations (Becker et al., 2011; Villatoro et al., 2014; Arns, Wahl, Haigh,

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Jensen, & Pattiaratchi, 2013; Demirbilek, 2013; PIANC Envicom - Task Group 3, 2008). Given that port activities naturally present substantial multiplier effect, disruptions due to climate on port logistic can drastically change the supply chain configuration (Dollar, Clark, & Micco, 2002; Loh & Thai, 2015) with major consequences on regional economy at large. Ports, therefore, require a unique forward-looking management approach to climate change based on port logistic resilience rather than infrastructure resistance (Mutombo & Ölçer, 2016). The proposed methodology in this paper offers a unique and practical tool for assessing and scoring climate resilience of port infrastructure within the broader context with the view to prioritise adaptive initiatives. Central to this process is the need to maintain seamless port logistic services when exposed to climate events; as a result of improved decision making. The paper begins with an overview on climate change and ports in section 2, followed by a brief literature review on climate adaptation on infrastructure under Section 3. Section 4 discusses the proposed methodology for scoring resilience and prioritising adaptive solutions. To demonstrate the applicability of the methodology, Section 5 presents a case study related to Port X; a real existing port under anonymity due to ethical considerations. Section 6 concludes the paper and provides some recommendations.

2. Climate change and ports.

As a result of a better understanding of climate processes, predictions of climate change have largely improved. Over the past 50years, observed global mean surface temperature trend has closely matched model simulations (IPCC, 2014). The IPCC predicts that global temperature for the end of the 21^{st} century is likely to exceed 1.5 °C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2 °C for scenarios RCP6.0 and RCP8.5. However, even if the world commits to significant greenhouse gas (GHG) emissions reductions, change to the current climatic process is unfortunately inevitable. The earth system will continue to experience sea level rise, droughts, floods, increase heat, intense storm and waves. Most common visible impacts of climate change on port infrastructure include failure of foundations, damage and deterioration to structures, inundation, increased wave overtopping, barrier material displacement and fracture, erosion, and increase in sediment inflow. Adapting port infrastructure to climate change has, therefore, become compelling and this is achieved by assessing the port ability to withstand climate variation, whereby thresholds of tolerance to climate variation are identified. These thresholds are then raised through adaptation (Burton, Diringer, & Smith, 2006). Despite the current availability of scientific and technical data in the industry, there is still presently no provision in the maritime industry for a port wide approach or methodology for assessing and incorporating these risks into port adaptation. Recommendations to incorporate sustainability into early stages of infrastructure development have been largely highlighted on many studies (Espinet, Schweikert, Heever, & Chinowsky, 2016; Araos et al., 2016); suggesting a holistic planning process taking into consideration asset life cycle assessments which include repairs and provision for alternatives. Such inclusive approach is known to substantially reduce financial costs from increased vulnerabilities, rehabilitation and additional maintenance (Espinet, Schweikert, Heever, & Chinowsky, 2016; Araos et al., 2016).

3. Literature review.

Often, politically-oriented responses to climate change aim at analysing and reviewing governance policies, legislative frameworks and institutional capacity (Australian Government, 2012; HM Government, ed., 2011; The World Association for Waterborne Transport Infrastructure, 2014; UNCTD Ad Hoc Expert Meeting, 2011; Kane, Vanderlinden, Baztan, Touili, & Claus, 2014). Although relevant to some extent, these responses have unfortunately not yielded any desired results (Transparency International, ed., 2011) due probably to the large disparity often experienced between policy intention and implementation on the field. Further to this, politically-oriented decisions on large infrastructure investments are largely speculated to be biased towards scoring points rather than addressing prevailing underlying issues (Transparency International, ed., 2011).

There is a general outcry in literature for the integration of adaptation actions and policy in order to achieve effective adaptation in practise (Adger, Arnell, & Tompkins, 2005). Yet, research on assessing climate change risk in port in the context of logistic chain is very limited. Although multi-objective risk analysis models for supply chains focussing on port-oriented intermodal cargo movement have been proposed in few literatures (Dollar, Clark, & Micco, 2002; Loh & Thai, 2015), they have however focussed mainly on one or two climate variables such as Sea level, wave, or wind. Moreover, due to the complex nature of climate change, most attempts to assess climate change in its entirety have rather been engineering oriented (RMIT University, 2013), focusing on port infrastructure resistance. Thus far, all attempts have shown some limitations, principally due to their silo approach. Increasingly, ports face a vast number of heterogenic stakeholders (Liu & Lam, 2015) due to their substantial multiplier effect. While the evaluation of a wider port logistic chain is progressively recognised (Liu & Lam, 2015; Loh & Thai, 2015), there are still major difficulties in developing an approach for assessing climate risk along such a complex network since stakeholders present discriminative risk exposure to climate events. This was also echoed by Adger et al (2005) who stress the importance of scale of implementation and the criteria for evaluation at each scale.

In the absence of a regulatory framework or methodology for assessing climate risks, ports often opt for customised climate adaptive solutions based on risk assessment conducted on individual prerogatives (Mutombo & Ölçer, 2016) without consideration to the wider logistic chain. Additionally, constant trade-off between cost and solutions (Hoggart et al., 2014) in the industry has been widely identified in many literature as a major hindrance to developing effective climate adaptations. Hence the need to prioritise. Very often, on account of cost constraint and in the absence of a systematic evaluation of climate risks, ports often favour short term mitigation rather than long term adaptation initiatives. This suggests large disparity in the perceptions of climate risks by decision makers which, according to Hopkins, Bailey, & Potts (2016), is the reason of the failure in successful implementation of adaptive solutions.

On the other hand, many authors have also highlighted the uncertainties surrounding projections of future climate change which make it difficult to accurately assess climate risk and develop adequate adaptive measures (Tompkins & Adger, 2005; Adger, Arnell, & Tompkins, 2005; Doria, Boyd, Tompkins, & Adger, 2009). With weak information, modelling actual climate risk in ports with probability-based theory is challenging (Luo & Caselton, 1997; Tompkins & Adger, 2005). As a result, response and adaptation to climate change often depend on individual decision-makers attitudes towards risk; thereby reinforcing the relevance of evaluating climate risk perceptions as an additional imperative.

Existing common management tools include (and not limited to) the followings: Cost benefit analysis, Multi criteria analysis and Cost efficiency analysis (Baum, 2012; Hoggart et al., 2014), Source-Pathway-Receptor (SPR) or Source-Pathway-Receptor-Consequences (SPRC) (Monbaliu et al., 2014; Villatoro et al., 2014), and outcome-based decision models focussing on low regret, no regret, win-win. Typically, these tools are based on scientific rationality, they evaluate real risks but they have proven to have weaknesses in the implementation which is mainly dependent on management climate risk perceptions. In addition, in many cases, they are not addressing the climate complexity in its entirety but rather focussing on few perceived climate variables likely to impact ports. In many instances, through these tools, assumptions are made that sea level rise, change rainfall and wind patterns, and extreme climate events (hurricanes, typhoons, cyclones, and tornados) are the prominent climate parameters. Although this trend is reflected in IPCC (2014) report, it may not necessarily be the case across all ports. Although existing management tools present significant benefits (Arns, Wahl, Haigh, Jensen, & Pattiaratchi, 2013; Kane, Vanderlinden, Baztan, Touili, & Claus, 2014), their relevance will however be discussed in the next paragraph when discussing the methodology.

In recent times, the search for better methods to deal with climate uncertainty has intensified with the development of new scientific tools, such as fuzzy set of theory, Dempser-Shafer theory and Bayesians methods (Luo & Caselton, 1997; Hobbs, 1997). These tools, which are known to be appropriate for dealing with uncertainties, rely mostly on sources of information (historical observations, experts opinion and model simulations) which are often not sufficiently available at this early stage of the climate change era. Additionally, the inability of Bayesian and fuzzy set of theory to represent a person state of knowledge and its incoherence and disconnect with human preferences (Hobbs, 1997) are some of the criticisms that make these tools inadequate in a corporate environment where actions are naturally driven by perceptions rather than rationality. On the other hand, to the authors? knowledge, there has not been any attempt in literature to factor potential length of port disruptions due to climate into resilience evaluation and this methodology aims to close this gap. Finally, there is an increasing consensus in literature to classify adaptation within three cornerstones (Adger, Arnell, & Tompkins, 2005; Doria, Boyd, Tompkins, & Adger, 2009; Tambo, 2016):

- Reduce the sensitivity of the system to climate. In the port context, this is principally achieved by factoring climate change in port design (PREPAREDNESS);
- Alter the exposure of the system to climate change. This entails making provision for redundancy and alternatives (ADJUST);
- Increase capacity to recover: This entails allowing short turnaround time for recovery (REBOUND BACK);

In the midst of these developments, challenges, and constraints, it is necessary to develop a decision making approach which satisfies the following fundamental requirements:

- *Inclusivity* - Take into consideration all relevant climate variables as possible.
- *Independence* - Mitigate any possibility of bias.
- *Effectiveness and efficiency* ? Ensure that adaptive initiatives achieve objectives while it also addresses the constant trade-off between cost and solutions.
- *Objectivity and Rationality* - Reduce as far as possible subjectivity arising from customised adaptive solutions resulting from silo decision making.
- *Usefulness* - Focus on moving goods as port priority function and mitigate any sense of exaggeration and over appreciation arising from the cultural nature of modern risk society which is more concerned with ?social bads? rather than "social goods" (Mythen, 2004).
- *Priority* - Prioritise scenarios presenting low resilience with respect to port primary function; i.e. movement of cargos.

The proposed methodology in this paper is a forward-looking management tool that aims at securing seamless port logistic services by satisfying the above fundamental requirements through the promotion of the following three (3) solution-focused cornerstone strategies: PREPAREDNESS - ADJUST - REBOUND BACK.

Moreover, in practical terms, these three strategies cannot always be optimally achieved at all times, often due to resources, environmental, geographical, strategic or political constraints; hence the need to prioritise based on resilience score.

4. Methodology.

It is believed in this study that effective adaptation to climate change in ports occurs when perceptions to climate risks are in tandem with the actual climate risk. In other words, decisions outcomes at strategic level in figure 1 shall be complemented through the evaluation of actual risk at project level.

While there are sufficient scientific tools to evaluate actual climate risks, this methodology focus on evaluating climate risk perceptions which ultimately inform management actions. It aims at equipping management with an additional tool for improving decision making when addressing climate change in ports at strategic level. Understanding the perceptions of those involved with decision making is important for understanding policy process (Hopkins, Bailey, & Potts, 2016; Tesfahunegn, Mekonen & Tekle 2016) and the success of management action in adapting ports to climate change.

As indicated earlier, contrary to the traditional short-sighted approach of focussing on resistance of assets or specific climate variable, the building of resilience in this case is explored along the logistic system in order to maintain free movement of goods across ports when exposed to various climate events. The ultimate objective of exploring opportunities within the PREPAREDNESS - ADJUST - REBOUND BACK set of strategies is to ensure that there are minimal (or no) climate induced disruptions to movement of cargoes through ports. When this objective is achieved, the system is considered as highly resilient to climate change.

4.1. Problem in context:

Adaptation projects should ideally be processed over two stages:

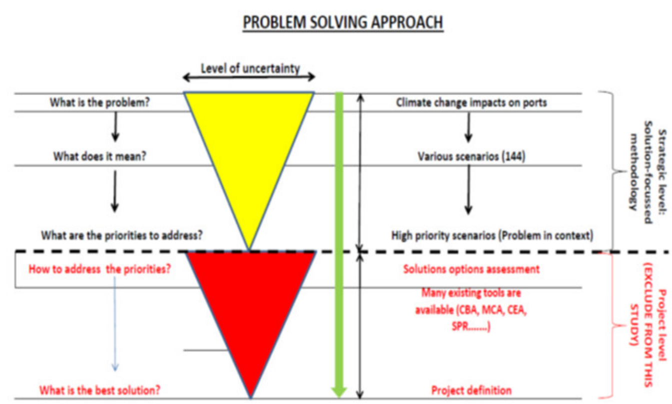
1. Identifying the right project (refer to Figure1 strategic level)
2. Doing the project right (refer to Figure1 project level)

As a project emerges from a need, the first stage requires a comprehensive assessment of the need to adapt to changing climate and possible consequences thereof. At this stage of identification, the problem or need in context appears fuzzy and this necessitates a thorough understanding of climate change in its entirety. Hence the need to breakdown climate complexities into a few solvable entities (scenarios) in order to prioritise needs (Figure 1). At this level, the evaluation is strictly based on management perceptions.

Once the problem or need has been clearly identified, various solutions can thereafter be explored with existing management tools at project level. Failure of existing management tools lies in the irrational manner the process of problem identification is done. This often result in wrong adaptation in projects implemented correctly; and this is the gap that this paper hopes to address. As shown on Figure 1, the proposed methodology is limited to addressing the first stage of adaptation process and existing management tools as discussed in literature review can then be used for the second stage after the problem or need has been clearly identified and contextualised.

A hypothetical example to strengthen this case is by using a metaphoric representation with the failure experienced by several ports in addressing congestion. The first stage in the identification of the underlying cause of the problem should ideally consist of evaluating whether the congestion is due to increase demand of goods, or inefficiency in operation, or navigation constraint, or climate. At this early stage, the cause of congestion is vague with high level of uncertainty. Although it was later found that in many cases port congestions are linked with inefficiency, management ironically and irrationally tends to link congestion with the increase demand of goods. As a result, solutions on whether to expand existing infrastructure or build new ports are then assessed using existing common tools; a typical case of wrong adaptation done correctly. Likewise, in the context of adaptation, management tends to replicate similar behaviours. Existing management tools are used with the assumption that sea level rise, change rainfall and wind patterns, and extreme climate events are the highest priorities. Meanwhile, there is however evidence that sea level is in fact decreasing in certain areas due the glacio-hydro-isostatic effects (Lambeck, 2001); and that salinity, humidity and water table were also found to be climate variables with major potential impacts on ports (RMIT University, 2013).

Figure 1: Complex problem solving approach.



Source: Authors.

4.2. Climate narrative and scenarios:

The objective of climate narrative and scenarios is to be able to address climate change and its impacts on ports in terms that are sufficiently descriptive and clear for qualitative evaluation. Climate extreme, known as climate event beyond projected threshold, is widely recognised as the biggest climate related threat to coasts in general (RMIT University, 2013; Macdonald & O'connor, 1996; Villatoro et al., 2014; Arns, Wahl, Haigh, Jensen, & Pattiaratchi, 2013; Oslakovic, Maat, Hartmann, & Dewulf, 2012; PIANC Envicom - Task Group 3, 2008) and port infrastructure in particular. This is generally a combination of abnormal increase in frequency or intensity of extreme proportions for particular climate variables (Hunter, Church, White, & Zhang, 2013). The nature of extreme events as a combination of multiple climate variables (Monbaliu et al., 2014) as well as the non-linear relationship between average and extremes weather make the building of resilience and adaptation initiatives very difficult to conceive and costly to achieve. In this paper, each climate variable should therefore be analysed in isolation and resilience for each needs to be built. Though there are likely to be increases in severity of extreme events (IPCC, 2014), the multiplier effect of these events however, is beyond the scope of this paper. Recommendations to design policies and management processes that are flexible, proactive and responsive to deal with extreme events are, therefore, emphasised (Kane, Vanderlinden, Baztan, Touili, & Claus, 2014) as a complement to this methodology.

Nevertheless, various studies have identified the following 8 major climate variables which would affect the long-term performance of port / coastal infrastructure: Sea level, water table, temperature, rainfall/runoff, waves, wind, salinity and humidity (RMIT University, 2013; Lewsey, C., Cid, G., & Kruse, E., 2004; Becker, A., Inoue, S., Fischer, M., & Schwegler, B., 2012; Chini & Stansby, 2012; Chini et al., 2010; Deepthi & Deo, 2010; Villatoro et al., 2014; Arns, Wahl, Haigh, Jensen, & Pattiaratchi, 2013; Kane, Vanderlinden, Baztan, Touili, & Claus, 2014; Demirbilek, 2013; Cox, Panayotou, Cornwel, & Blacka, 2014).

Moreover, berthing structure, protection barriers, port superstructures, channels and harbour basins, road infrastructure and rail infrastructure are identified as the 6 most well-known and obvious components of port infrastructure on which climate change has a direct impact (RMIT University, 2013). A scenario in this study is defined as the exposure of a port family asset to a particular climate variable event within a short, medium or long term horizon. In this respect, the total number of scenarios considered in this study are shown in equation 1 and table 1:

8 Climate variables x 6 port infrastructure families x 3 time horizons = 144 scenarios (1)

Table 1: Calculation of number of scenarios.

Protection barriers	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
Channels & basins	33	34	35	36	38	39	40	41
Berthing structure	25	26	27	28	30	31	32	33
Port superstructure	17	18	19	20	21	22	23	24
Road network	9	10	11	12	13	14	15	16
Rail network	1	2	3	4	5	6	7	8
	Sea level rise	**Water table**	**Temperature**	**Rainfall**	**Wave**	**Wind**	**Salinity**	**Humidity**

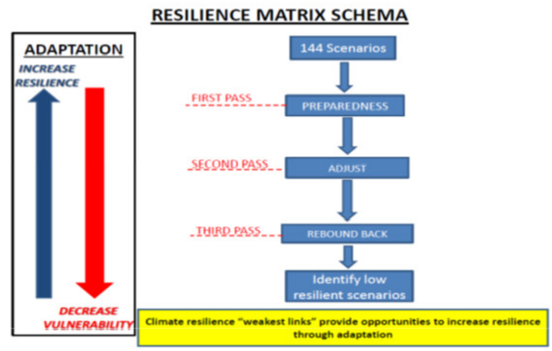
Source: Authors.

Because each port is unique and located in a distinctive geographical location, a specific climate narrative should be developed for each port. This is essential and forms the basis for resilience assessment.

4.3. Methodology by resilience matrix:

Based on the fundamental requirements, the methodology by resilience matrix (Figure 2) sets the problem into context in order to address it. In light of the complexities posed by climate change, a "divide and conquer" problem-solving strategy (Jordan, 2013) is necessary to break down complexities into small solvable problems which are hereby referred as scenarios. Resilience of the 144 original scenarios (Figure 3) are therefore assessed and scored throughout the three (3) different layers of filters: PREPAREDNESS, ADJUST AND REBOUND BACK (Figure 2).

Figure 2: Methodology by Resilience Matrix (Colour printing).



Source: Authors.

An increase in port resilience is achieved by implementing these three sets of actions: planning, redundancy and flexibility (NCFRP, 2014). "Preparedness" remains the best strategy rather than "Adjust" or "Recover" after a disaster (Liao, 2012). For this reason, an allocation of weights for Preparedness, Adjust and Recovery is respectively 50%, 25% and 25% on the resilience matrix (Table 2) which reflects correctly with the views of port experts that were interviewed during the study. In addition, this trend is supported by many literature that promote preparedness as the most important natural response and first line of defence to climate change (Adger, Arnell, & Tompkins, 2005; Doria, Boyd, Tompkins, & Adger, 2009; Tambo, 2016). Moreover, each port may choose to alter the weights as they deem necessary; depending on the size and nature of their activities as well as their configurations and exposure to climate risks.

- **Preparedness**: Prior actions geared to avoiding and limiting disruption?s impacts.. Factoring climate change parameters during infrastructure design earns automatically the full 50% score on the resilience matrix. Contrary, no score is earned when such allowance was not made.

- **Response or Adjust**: Actions geared to dealing with the immediate impacts of the disruptions. Research has shown that port capacity expansion is essential for the disruption management of port oriented transportation networks (Loh & Thai, 2015). This can be conceptualised as the ability to remain in a desirable regime of logistic service by making the necessary adjustment in the system while experiencing climate induced damages. It consists of evaluating whether there is availability of alternatives or redundancy. If such provision exists, a full 25% score is automatically earned on the resilience matrix. It is worth noting that Redundancy is more than duplication; it entails diversity and functional replication across scales (Liao, 2012). For example when a rail line that serves the port is impacted, road could be used as suitable alternative. Similarly, rerouting cargoes to a back-up port could also be considered as a suitable alternative if it does not significantly affect the entire logistic chain configuration.

- **Recovery or Rebound Back**: Actions geared to getting the port back up and running again as soon as possible. In addition to preparedness and responsiveness, the ability to recover from climate induced damages is essential in order to maintain port logistic service. Rare and periodic climate induced damages are opportunities for ports to become better fit and increase resilience. Disruptions in ports can have a wide range of potential negative impacts on its transportation networks (Liu & Lam, 2015); while sometimes also benefit other ports in close proximity. Such impacts are expected to be further magnified by the wide adoption of lean operations and just-in-time practise of modern supply chains.

  Moreover, while disruptions provide opportunities for improving resilience, they seriously impact the logistic services with detrimental effects to the broader context. For this reason, in logistic context, potential time of recovery after a disaster is an essential factor in order to mitigate risk of further losses. The ability of a system to recover immediately after disaster earns a maximum score 25% and the longer it takes to recover progressively reduces the score.

  Generally, goods are transported through a primary port, and possibly a back-up port. When disruption occurs, the primary port is likely to develop a backlog of goods that will not dissipate unless the port reopens, or contingency rerouting is implemented via back up ports. This often gets managed seamlessly for a short period disruption. However, with longer disruptions, back logs may cascade from the first back up port, to a second and so on, thereby magnifying impacts which often result in exponential increase in loss as disruptions persist. As such, on the resilience matrix (Table 2), the score under recovery is a function of the weight (25%) and time of recovery (t). Defining resilience as a function of time of recovery is one of the originality of this methodology. Maximum resilience of a scenario (under the recovery category) is achieved when time of recovery is minimised or null. The longer the potential time of recovery after disruptions, the lesser the resilience for a particular scenario. Loss due to disruptions is in turn an exponential function of time of recovery. If x is the loss incurred by climate disruptions over time t, therefore x depends exponentially on time t:

  $$x(t) = a.b^{[t/\pi]} \qquad (2)$$

  Where a is the constant which reflects the loss during the time (month) of disruption when t=0:

  $$x(0) = a \qquad (3)$$

  The constant b is a positive growth factor, and τ is the time constant (the time interval for x to increase by a factor of b). (If $\tau > 0$ and b > 1, then x has exponential growth. If τ 0 and b > 1, or $\tau > 0$ and 0 < b < 1, then x has exponential decay). Under the recovery strategy, it was shown that there is an exponential decay relationship between resilience and loss incurred (x), which suggests that $\tau < 0$ since b>1. Resilience score will therefore be dependent on the variable $b^{t/\tau}$:

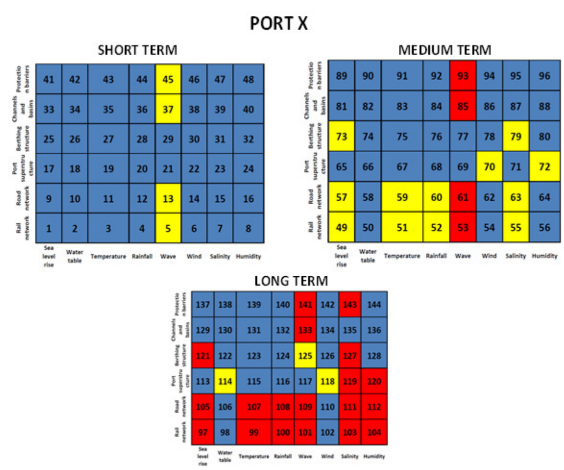
  $$Resilience\ score_r = weight \times (b)^{t/\tau} \qquad (4)$$

  In practical term, loss due to climate disruptions in ports significantly differ from one port to another, depending on the nature, size, characteristic and configuration of the port. For the purpose of this case study, assumptions are made that the loss due to climate disruptions in ports doubles (b = 2) every month (τ = -1), then:

  $$Resilience\ score_r = weight \times (0.5)^t \qquad (5)$$

  Resilience scorer = weight x (0.5) Equation 5

Figure 3: 144 scenarios representation.



Source: Authors.

Ultimately, the resilience matrix (Table 2) is developed in a way that mitigates the following risks:

- *Non-Adaptation*: Factoring future climate predictions into port infrastructure design is the best strategy for building resilience. This is known as the first pass on the resilience matrix. In other words, the first pass alerts stakeholders on areas of danger (Kane, Vanderlinden, Baztan, Touili, & Claus, 2014) requiring special attention. Various studies suggest that the cost of climate risk is in most case estimated to be higher than the cost of adaptation (The World Bank, 2010; Hoggart et al., 2014).

- *Mal-Adaptation*: While there could be many areas of danger, not all areas require the same level of attention. Considering the constant trade-off between cost and adaptive solution (Becker, Inoue, Fischer, & Schwegler, 2012; Hoggart et al., 2014; Ölçer & Ballini, 2015), it is crucial to evaluate further each area or scenarios and prioritise based on severity, which is reflected by a low resilience. This is the relevance and particularity of the second pass and third passes; the ability to adjust and rebound back. Ultimately the remaining two passes ensure that adaptation is achieved where mostly needed; thereby mitigating risk of mal-adaptation.

- *Over-Adaptation*: The current rising tide of cultural anxiety towards risk (Mythen, 2004) and the insatiable need for visibility in political sphere may lead to unnecessary adaptation (over adaptation) unless a rational assessment is performed to assess such need. Some literatures warned against the risk of over investment in unnecessary resilience which is seen as greater than the risk of failure (The Royal Academy of Engineering, Ed., 2011). Hence the relevance of an effective resilience matrix.

Although this solution-oriented approach may prove to be very effective in identifying adaptation priorities; Cox, Panayotou, Cornwel & Blacka (2014) paradoxically warned about the danger of the mono-directional focus of risk assessments which may potentially generate consequences to broader context. In the proposed approach, there are indeed climate impacts such as increased in maintenance, operation and insurance costs, adverse reputational and safety impact, environmental and regulatory impacts which are not visibly and directly affecting port logistic over a short and medium timeframe period, and will therefore not receive the necessary attention in this methodology. This prompts the need to emphasise the relevance of this methodology developed with the immediate view of maintaining port business continuity rather than addressing long term business sustainability. Nevertheless, the close relation between concepts of business continuity and sustainability cannot be refuted, thereby reinforcing the significance of this methodology as an important and additional consideration in the context of long term port business sustainability. Further to this, taking into account the concept of infrastructure interdependencies (HM Government, ed., 2011), this approach presents some limitations since the port cannot control any climate induced failure outside port boundaries with cascading effect inside the port. Although there is a wide acknowledgement in the industry of the need for port to partner closely with the city on planning issues, interdependencies create an amount of risk that ports should accept to live with.

5. Case Study on Port X.

5.1. Climate narrative and scenarios for Port X:

The development of scenarios facilitates communication on climate risks (LTAS, 2015) and highlights opportunities for building resilience by allowing qualitative assessments of risks in addition to technical and quantitative assessments. A brief analysis of climate change trends and projections for Port X region was conducted and was compared with model projections for the same time period. This resulted in the development of a consensus view of climate narrative (Table 2) for short, medium and long term to be used in the context of this study. For instance, medium and long term trends in temperature and sea level related indices are generally clearer than trends in rainfall, wave, wind salinity, humidity and water table indices; this also reflects in IPCC WGII AR5 document. This is further reflected on the proposed climate narrative Table 1 whereby hypothetical percentage ranges have been used for all uncertain climate projections. Due to the preventive nature of this approach, larger projection ranges (such as a change greater than 100%) are used as a conservative way to factor uncertainty and to allow sufficient safety window when addressing climate risks. However, given that such allowances may sometimes appear unrealistic, each port may choose to revise this climate narrative to suit its own specific circumstances. Moreover, as climate modelling improves, more accuracy will be achieved in developing climate narrative.

Table 2: Climate Narrative.

CLIMATE VARIABLES	UNIT	PROJECTED VARIATION		
		Short term (up to 7 years)	Medium term (50 years)	Long term (100 years)
Sea Level Rise	m	0.1m	0.75m	1.5m
Water table	m	<1m	5m	>10m
Temperature	Deg	0.3°c	1.0°c	2°c
Rainfall	%	<10%	50%	>100%
Wave height	%	<10%	50%	>100%
Wind speed	%	<10%	50%	>100%
Ocean salinity	%	<10%	50%	>100%
Humidity	%	<10%	50%	>100%

Source: Authors.

Table 3: Resilience matrix.

LONG TERM SCENARIOS																			
	PREPAREDNESS (P)				ADJUST (A)				REBOUND BACK (R)										
	Design factors future climate conditions (P=1 for Yes and P=0 for No)		Weight$_p$	Score$_p$	In case of disruption, any immediate alternative that could maintain movement of goods (A=1 for Yes and A=0 for No)		Weight$_a$	Score$_a$	The anticipated duration required in months to repair and get the asset back to functionality in order to allow smooth movement of goods.								Weight$_r$	Score$_r$	Total Resilience score
Scenarios	YES (1)	NO (0)	50%	$W_p \times P$	YES (1)	NO (0)	25%	$W_a \times A$	t								25%	$W_r / (t^2 + 1)$	Score$_{(p+a+r)}$
									0	1	2	3	4	5	6	X			
1			50%				25%										25%		
2			50%				25%										25%		
3			50%				25%										25%		
4			50%				25%										25%		
			50%				25%										25%		
			50%				25%										25%		
			50%				25%										25%		
			50%				25%										25%		
			50%				25%										25%		
			50%				25%										25%		
			50%				25%										25%		
141			50%				25%										25%		
142			50%				25%										25%		
143			50%				25%										25%		
144			50%				25%										25%		

Source: Authors.

5.2. Resilience score results:

Table 4, 5 and 6 present respectively short, medium and long term resilience score results for Port X.

5.3. Results summary and brief discussions:

Short term results (Table 4):

Over short term, there is no cause for concern. All scenarios (1 to 48) present a satisfactory resilience score of over 50%. Moreover, there is a visible trend showing high resilience

Table 4: Short term results for Port X.

SHORT TERM SCENARIOS

		PREPAREDNESS (P)				ADJUST (A)				REBOUND BACK (R)										Total Resilience score
		Design parameters developed to resist future conditions		Weight_p	Score_p	disruption, any immediate alternative that could maintain movement of goods		Weight_a	Score_a	Anticipated time of recovery in month (t)								Weight_r	Score_r	
	Scenarios	YES (1)	NO (0)	50%	W_p X P	YES (1)	NO (0)	25%	W_a X A	0	1	2	3	4	5	6	X	25%	W_r x (0,5)^t	Score (a+b+c)
RAIL NETWORK	1	1		50%	50%	1		25%	25%				3					25%	3%	78%
	2	1		50%	50%	1		25%	25%				3					25%	3%	78%
	3	1		50%	50%	1		25%	25%		1							25%	13%	88%
	4	1		50%	50%	1		25%	25%							6		25%	0%	75%
	5	1		50%	50%	1		25%	25%				3					25%	3%	78%
	6	1		50%	50%	1		25%	25%				3					25%	3%	78%
	7	1		50%	50%	1		25%	25%		1							25%	13%	88%
	8	1		50%	50%	1		25%	25%		1							25%	13%	88%
ROAD NETWORK	9	1		50%	50%	1		25%	25%			2						25%	6%	81%
	10	1		50%	50%	1		25%	25%			2						25%	6%	81%
	11	1		50%	50%	1		25%	25%	0								25%	25%	100%
	12	1		50%	50%	1		25%	25%			2						25%	6%	81%
	13	1		50%	50%	1		25%	25%			2						25%	6%	81%
	14	1		50%	50%	1		25%	25%		1							25%	13%	88%
	15	1		50%	50%	1		25%	25%	0								25%	25%	100%
	16	1		50%	50%	1		25%	25%	0								25%	25%	100%
SUPERSTRUCTURE	17	1		50%	50%	1		25%	25%				3					25%	3%	78%
	18	1		50%	50%	1		25%	25%								12	25%	0%	75%
	19	1		50%	50%	1		25%	25%							6		25%	0%	75%
	20	1		50%	50%	1		25%	25%							6		25%	0%	75%
	21	1		50%	50%	1		25%	25%				3					25%	3%	78%
	22	1		50%	50%		0	25%	0%							6		25%	0%	50%
	23	1		50%	50%	1		25%	25%		1							25%	13%	88%
	24	1		50%	50%	1		25%	25%		1							25%	13%	88%
BERTHS	25	1		50%	50%		0	25%	0%								12	25%	0%	50%
	26	1		50%	50%		0	25%	0%								12	25%	0%	50%
	27	1		50%	50%		0	25%	0%				3					25%	3%	53%
	28	1		50%	50%		0	25%	0%							6		25%	0%	50%
	29	1		50%	50%	1		25%	25%							6		25%	0%	75%
	30	1		50%	50%		0	25%	0%				3					25%	3%	53%
	31	1		50%	50%		0	25%	0%				3					25%	3%	53%
	32	1		50%	50%		0	25%	0%				3					25%	3%	53%
CHANNELS & BASINS	33	1		50%	50%		0	25%	0%								12	25%	0%	50%
	34	1		50%	50%		0	25%	0%								12	25%	0%	50%
	35	1		50%	50%		0	25%	0%								12	25%	0%	50%
	36	1		50%	50%		0	25%	0%				3					25%	3%	53%
	37	1		50%	50%		0	25%	0%				3					25%	3%	53%
	38	1		50%	50%		0	25%	0%								12	25%	0%	50%
	39	1		50%	50%		0	25%	0%						5			25%	1%	51%
	40	1		50%	50%		0	25%	0%						5			25%	1%	51%
PROTECTION BARRIERS	41	1		50%	50%		0	25%	0%								12	25%	0%	50%
	42	1		50%	50%		0	25%	0%								12	25%	0%	50%
	43	1		50%	50%		0	25%	0%				3					25%	3%	53%
	44	1		50%	50%		0	25%	0%								12	25%	0%	50%
	45	1		50%	50%		0	25%	0%								12	25%	0%	50%
	46	1		50%	50%		0	25%	0%								12	25%	0%	50%
	47	1		50%	50%		0	25%	0%				3					25%	3%	53%
	48	1		50%	50%		0	25%	0%				3					25%	3%	53%

TOWARDS LAND SIDE ↑ / TOWARDS SEA SIDE ↓

Source: Authors.

Table 5: Medium term results for Port X.

MEDIUM TERM SCENARIOS

		PREPAREDNESS (P)				ADJUST (A)				REBOUND BACK (R)										Total Resilience score
		Design parameters developed to resist future conditions		Weight_p	Score_p	In case of disruption, any immediate alternative to maintain movement of goods		Weight_a	Score_a	Anticipated time of recovery in month (t)								Weight_r	Score_r	
	Scenarios	YES (1)	NO (0)	50%	W_p X P	YES (1)	NO (0)	25%	W_a X A	0	1	2	3	4	5	6	X	25%	W_r x (0,5)^t	Score (a+b+c)
RAIL NETWORK	49	1		50%	50%	1		25%	25%					4				25%	2%	77%
	50	1		50%	50%	1		25%	25%					4				25%	2%	77%
	51	1		50%	50%	1		25%	25%				3					25%	3%	78%
	52	1		50%	50%	1		25%	25%							6		25%	0%	75%
	53		0	50%	0%	1		25%	25%					4				25%	2%	27%
	54	1		50%	50%	1		25%	25%					4				25%	2%	77%
	55	1		50%	50%	1		25%	25%			2						25%	6%	81%
	56	1		50%	50%	1		25%	25%			2						25%	6%	81%
ROAD NETWORK	57	1		50%	50%	1		25%	25%			2						25%	6%	81%
	58	1		50%	50%	1		25%	25%			2						25%	6%	81%
	59	1		50%	50%	1		25%	25%	0								25%	25%	100%
	60	1		50%	50%	1		25%	25%			2						25%	6%	81%
	61		0	50%	0%	1		25%	25%			2						25%	6%	31%
	62	1		50%	50%	1		25%	25%		1							25%	13%	88%
	63	1		50%	50%	1		25%	25%	0								25%	25%	100%
	64	1		50%	50%	1		25%	25%	0								25%	25%	100%
SUPERSTRUCTURE	65	1		50%	50%	1		25%	25%				3					25%	3%	78%
	66	1		50%	50%	1		25%	25%								12	25%	0%	75%
	67	1		50%	50%	1		25%	25%							6		25%	0%	75%
	68	1		50%	50%	1		25%	25%							6		25%	0%	75%
	69	1		50%	50%	1		25%	25%				3					25%	3%	78%
	70	1		50%	50%		0	25%	0%							6		25%	0%	50%
	71	1		50%	50%	1		25%	25%			2						25%	6%	81%
	72	1		50%	50%	1		25%	25%			2						25%	6%	81%
BERTHS	73	1		50%	50%		0	25%	0%								12	25%	0%	50%
	74	1		50%	50%		0	25%	0%								12	25%	0%	50%
	75	1		50%	50%		0	25%	0%					4				25%	2%	52%
	76	1		50%	50%		0	25%	0%							6		25%	0%	50%
	77	1		50%	50%	1		25%	25%							6		25%	0%	75%
	78	1		50%	50%		0	25%	0%							6		25%	0%	50%
	79	1		50%	50%		0	25%	0%					4				25%	2%	52%
	80	1		50%	50%		0	25%	0%					4				25%	2%	52%
CHANNELS & BASINS	81	1		50%	50%		0	25%	0%								12	25%	0%	50%
	82	1		50%	50%		0	25%	0%								12	25%	0%	50%
	83	1		50%	50%		0	25%	0%								12	25%	0%	50%
	84	1		50%	50%		0	25%	0%					4				25%	1%	51%
	85		0	50%	0%		0	25%	0%					4				25%	2%	2%
	86	1		50%	50%		0	25%	0%								12	25%	0%	50%
	87	1		50%	50%		0	25%	0%						5			25%	1%	51%
	88	1		50%	50%		0	25%	0%						5			25%	1%	51%
PROTECTION BARRIERS	89	1		50%	50%		0	25%	0%								12	25%	0%	50%
	90	1		50%	50%		0	25%	0%								12	25%	0%	50%
	91	1		50%	50%		0	25%	0%						5			25%	1%	51%
	92	1		50%	50%		0	25%	0%								12	25%	0%	50%
	93		0	50%	0%		0	25%	0%								12	25%	0%	0%
	94	1		50%	50%		0	25%	0%								12	25%	0%	50%
	95	1		50%	50%		0	25%	0%					4				25%	2%	52%
	96	1		50%	50%		0	25%	0%					4				25%	2%	52%

TOWARDS LAND SIDE ↑ / TOWARDS SEA SIDE ↓

Source: Authors.

score for land based infrastructure (Road, rail and superstructure) which progressively reduces towards sea based infrastructure (Berths, channels and protection barriers). This suggests that exposure to climate risk is greater on sea side and progressively reducing towards land side. This information should steer the way climate adaptation investments are allocated in ports and it should also provide significant guidance to design engineers when factoring climate change in infrastructure design calculations.

Medium term results (Table 5):

Results for medium term reveal two scenarios of high concern and two scenarios of moderate concern. Scenarios 85 and 94 score respectively 2% and 0% on resilience and this needs immediate management attention. Moreover, although scenarios 53 and 61 present respectively scores of 27% and 31% on resilience, actions on these scenarios will solely be dependent on management decisions based on several factors such as funds availability, management risk appetite, management style, etc. Threshold for requiring immediate actions shall be set by management. Meanwhile, the trend showing the reduction in resilience score from land side to sea side infrastructure is still visible, though to a lesser extent.

Long term results (Table 6):

Over long term, there are several concerning scenarios: 97, 99, 100, 101, 103, 104, 105, 108, 109, 119, 120, 121, 127, 133, 141 and 143. Among these, scenarios 121, 127, 133, 141 and 143 are the most concerning, scoring respectively 0%, 2%, 1%, 0% and 0%.

Whilst most concerning scenarios relate to sea-side infrastructure, there is however a shift in the overall trend pattern in comparison to short and medium term results. Results of long term scenarios indicate that low resilience scores (in red) are evenly distributed across sea side and land side infrastructure; with an average tendency of a relatively higher resilience towards sea side (less red colour). This is probably attributed to the shorter design life of land side based infrastructure in comparison to sea side based infrastructure which are long life; generally 50 to 100years with greater safety factor. This should trigger new ways of thinking with respect to port configuration and design approach during early planning stage of port development.

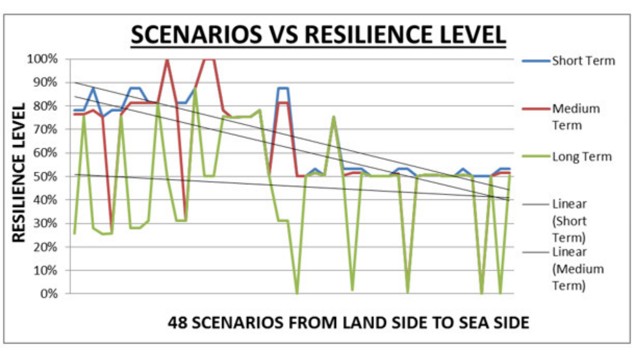
On Figure 4, the short disparity between short and medium term trend lines further suggest that, in contrast to specific pocket of scenarios which may be significantly affected by time scale, timescale do not significantly affect port climate resilience in general. Therefore, individual?s efforts to combat climate specific events may be worthwhile rather than general climate actions at larger scale which are often policy based. In contrast, considering the long term trend line, more considerations shall be given to policy driven actions at larger scale to address long term climate scenarios rather than individual actions.

Table 6: Long term results for Port X.

	LONG TERM SCENARIOS																				
		PREPAREDNESS (P)				ADJUST (A)				REBOUND BACK (R)											
		Design parameters developed to resist future conditions		$Weight_p$	$Score_p$	In case of disruption, any immediate alternative to maintain movement of goods		$Weight_a$	$Score_a$	Anticipated time of recovery in month								$Weight_r$	$Score_r$	Total Resilience score	
										t											
	Scenarios	YES (1)	NO (0)	50%	W_p X P	YES (1)	NO (0)	25%	W_a X A	0	1	2	3	4	5	6	X	25%	W_r x $(0,5)^t$	Score $_{(a+b+c)}$	
RAIL NETWORK	97		0	50%	0%	1		25%	25%						5			25%	1%	26%	TOWARDS LAND SIDE
	98	1		50%	50%	1		25%	25%						5			25%	1%	76%	
	99		0	50%	0%	1		25%	25%				3					25%	3%	28%	
	100		0	50%	0%	1		25%	25%							6		25%	0%	25%	
	101		0	50%	0%	1		25%	25%						5			25%	1%	26%	
	102	1		50%	50%	1		25%	25%						5			25%	1%	76%	
	103		0	50%	0%	1		25%	25%				3					25%	3%	28%	
	104		0	50%	0%	1		25%	25%				3					25%	3%	28%	
ROAD NETWORK	105		0	50%	0%	1		25%	25%			2						25%	6%	31%	
	106	1		50%	50%	1		25%	25%			2						25%	6%	81%	
	107		0	50%	0%	1		25%	25%	0								25%	25%	50%	
	108		0	50%	0%	1		25%	25%			2						25%	6%	31%	
	109		0	50%	0%	1		25%	25%			2						25%	6%	31%	
	110	1		50%	50%	1		25%	25%		1							25%	13%	88%	
	111		0	50%	0%	1		25%	25%	0								25%	25%	50%	
	112		0	50%	0%	1		25%	25%	0								25%	25%	50%	
SUPERSTRUCTURE	113	1		50%	50%	1		25%	25%						5			25%	1%	76%	
	114	1		50%	50%	1		25%	25%								12	25%	0%	75%	
	115	1		50%	50%	1		25%	25%							6		25%	0%	75%	
	116	1		50%	50%	1		25%	25%							6		25%	0%	75%	
	117	1		50%	50%	1		25%	25%				3					25%	3%	78%	
	118	1		50%	50%		0	25%	0%							6		25%	0%	50%	
	119		0	50%	0%	1		25%	25%			2						25%	6%	31%	
	120		0	50%	0%	1		25%	25%			2						25%	6%	31%	
BERTHS	121		0	50%	0%		0	25%	0%								12	25%	0%	0%	TOWARDS SEA SIDE
	122	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	123	1		50%	50%		0	25%	0%					4				25%	2%	52%	
	124	1		50%	50%		0	25%	0%							6		25%	0%	50%	
	125	1		50%	50%	1		25%	25%							6		25%	0%	75%	
	126	1		50%	50%		0	25%	0%							6		25%	0%	50%	
	127		0	50%	0%		0	25%	0%					4				25%	2%	2%	
	128	1		50%	50%		0	25%	0%					4				25%	2%	52%	
CHANNELS & BASINS	129	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	130	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	131	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	132	1		50%	50%		0	25%	0%						5			25%	1%	51%	
	133		0	50%	0%		0	25%	0%						5			25%	1%	1%	
	134	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	135	1		50%	50%		0	25%	0%						5			25%	1%	51%	
	136	1		50%	50%		0	25%	0%						5			25%	1%	51%	
PROTECTION BARRIERS	137	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	138	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	139	1		50%	50%		0	25%	0%						5			25%	1%	51%	
	140	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	141		0	50%	0%		0	25%	0%								12	25%	0%	0%	
	142	1		50%	50%		0	25%	0%								12	25%	0%	50%	
	143		0	50%	0%		0	25%	0%							6		25%	0%	0%	
	144	1		50%	50%		0	25%	0%							6		25%	0%	50%	

Source: Authors.

Figure 4: Trend lines.



Source: Authors.

Meanwhile, there are also indications that most priorities (low resilience) scenarios are long term and management may therefore perceive them as non-immediate priorities and may rather select to address relatively higher resilience score scenarios on short or medium term. Assessing whether a relatively higher resilience score scenario over short term should be prioritised in lieu of a lower resilience score scenario over long term could be extremely tedious and ambiguous; and outcome-based decision models focussing on low regret, no regret and win-win could possibly be used in this regard. Such decision may heavily be influenced by the perceived degree of accuracy of predictions on climate narrative table. In this case study, given the high climate projection uncertainty, the conservative approach used in developing the climate narrative may justify reservations with long term low resilience score scenarios in favour of medium or short term scenarios presenting moderate resilience score. Finally, as high priority scenarios (low resilience) are now identified as problems in context, projects could then be initiated and solutions options be assessed using existing tools (Cost-benefit analysis, Multi-criteria analysis, Cost-efficiency analysis etc.) as per lower part of Figure 1.

Conclusions

A significant contribution of this methodology lies in its attempt to align risk perceptions, management actions and policy processes in order to achieve successful climate adaptation in ports. Failure of existing tools that deal with uncertainty are due to their inabilities to represent a person state of knowledge and preferences.

Adaptations which consisting of increasing resilience of vulnerable scenarios will require actions within these 3 cornerstones: Preparedness, Adjust and Recovery strategies. Such actions will require to be implemented holistically under any of the three pillars of adaptations which are known as technology, management, and policy (Mutombo & Ölçer, 2016). While technology and management actions are adequate to generate individual port benefits, efforts to implement policy will tend to tackle issue of interdependency at national scale but with cascading effect into the port precinct. Moreover, given that some actions may have externalities elsewhere, the cross-scale dynamics for effectively implementing these 3 strategies may prove challenging unless a thorough analysis of all port stakeholders is well-understood.

Meanwhile, it was found from the proposed methodology that, like any other tool, there are some limitations in its application. These limitations are particularly the results of the challenges associated with interdependencies, extreme weather events, and with the mono-directional focus of risk assessment. Moreover, relevance of the proposed methodology lies principally at high strategic level of decision making, whereby climate change needs to be contextualised within ports. It shall be used as an effective tool for ensuring that the correct climate priorities are identified and existing tools may thereafter be used to ensure that relevant adaptation projects are implemented correctly. Recommendations to use this methodology in complementarity with existing policies and management tools are therefore emphasised.

It is worth noting that, although this paper demonstrates the applicability of the developed approach to a specific case of Port X; with the right tailoring, this methodology can be effectively used in assessing climate risks and prioritizing solutions on any logistic chain worldwide. Further to this, while this methodology focuses at port development stage, it may certainly assist management in improving decision making during port retrofitting and maintenance related projects. Finally, the reliability of this methodology heavily depends on the development of a realistic climate narrative. In this paper, a brief analysis of climate change trends and projections for Port X region was conducted and was compared with model projections for the same time period and this resulted in the consensus view of climate narrative over short, medium and long term. However, as additional recommendations to this framework, an assessment of the strengths and weaknesses of modelled projections should ideally be presented to guide future adaptation initiatives. This will provide a qualitative basis for assessing the credibility of future projections, and to guide efforts to address shortcomings; thereby improving reliability of results.

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