Modelling risk based cost analysis of port adaptation measures to climate change

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Abstract

This paper presents a techno-economic modelling methodology that can be applied to the economic analysis of port climate change adaptation measures based on risk analysis. The proposed methodology brings together risk and cost criteria into the decision making process for the improvement of port adaptation policies. Information produced using a subjective fuzzy risk analysis approach is utilised to construct such a techno-economic model. An evidential reasoning approach is then employed to synthesis the risk analysis results and economic evaluation of port adaptation measures to process the constructed model. The results produced can assist policymakers in developing efficient adaptation measures that take into account the reduction of probabilistic risks, their possible consequences, their timeframe, as well as the need of costs incurred. A technical example of risk-based economic analysis of adaptation measures in an American port is presented to demonstrate the interaction between economic modelling and risk analysis and to indicate the potential use of this methodology in the climate change adaptation decision-making process of port systems. The results of the paper will provide important insight to the maritime community as to how to develop efficient climate change adaptation measures in a wider supply chain context to ensure maritime transportation sustainability.

Key words: Climate change, port adaptation, maritime risk, techno-economic modelling, multiple criteria decision making

1. Introduction

Climate change is at the forefront of research across disciplines due to its potential catastrophic risks to human welfare (Keohane and Victor, 2010). It is argued that climate change is an irreversible process, which could lead to the catastrophic climate change-related risks posed to human lives and activities, as exemplified by hurricanes Katrina and Sandy's impacts to the North American coastline in the last several years. Hence, the study of climate change is moving from purely mitigation focus towards an orientation of addressing mitigation and adaptation simultaneously.

In this regard, ports are highly vulnerable to such risks in terms of both their facilities and operations (Becker et al., 2012). Given the critical role that ports play in the global economy and supply chains (Ng and Liu, 2014), their inability to successfully adapt to climate change risk poses a significant problem in our contemporary world. Thus, it is very important to find effective ways for ports to adapt to the challenges posed by climate change, and this requires a concerted effort by stakeholders in providing global and local perspectives, bridging the gap between local-level experiences and international/national decision-making frameworks. Policymakers and port stakeholders must understand potential risks to ports so as to undertake appropriate adaptation planning and strategies. However, the impact of climate change on ports remains very unclear, and is subject to diverse interpretations from different stakeholders and across geographical regions. Also, most ports are under financial constraints, complicating decisions about when, how and to what extent appropriate strategies and capacity investments should be committed, in order to successfully adapt to this new but highly uncertain reality. Although there is an urgent demand for the development of knowledge and optimal solutions to assist ports in assessing the relationship between climate change risks and adaptation strategies, so far, little research has been undertaken. Such a scarcity is reflected by the repeated call by many inter-governmental organizations, such as the United Nations Conference on Trade and Development (UNCTAD) and the European Commission, to develop and share international best practices in this area (see UNCTAD, 2012; ECJRC, 2013).

Understanding such deficiency, the purpose of the paper is to better understand the risks posed by climate change on ports, and how to effectively adapt to and manage such risks. The partners have two main objectives. First, it strives to understand how port stakeholders use risk-reduction strategies and evidence-based adaptations to deal with climate change risks. Second, it develops an analytical model to generate best practices for providing appropriate long-term resilience and adaptation to climate change risks. It will be one of the first of its kind to examine the major risks to ports posed by climate change, and how adaptation planning can be rationally developed through the exchange of knowledge and expertise among researchers and port stakeholders in the global context. It offers vital information on how to enhance human resilience against climate change risks effectively, and will greatly improve the ability of ports to tackle the uncertainties in responding to these risks. The outcomes of this proposed study will be of considerable value to port planners, policymakers and industrial practitioners, helping them to create and implement adaptation plans, strategies and practices.

The rest of the paper is structured as follows. The literature review can be found in section 2. The risk economic model will be presented in section 3. In section 4, the data collected from the studied port will be described, and followed by the model's calibration. Finally, the conclusion, including its contribution and revelation for further research, can be found in section 5.

2. Literature review

2.1 Port adaptation to climate change

There is no shortage of research investigating climate change risks, notably sea level rise (SLR) (e.g., Jevrejeva et al. 2012; Liu 1997; Schaeffer et al. 2012), vulnerability of coastal areas (e.g., McGinnis and McGinnis 2011; Nicholls and Hoozemans 1996; Shea and Dyoulgerov 1997) and constructing coastal defenses through marine eco-systems (Chemane et al. 1997; Tobey et al. 2010). Many illustrate the urgency for mitigation and adaptation plans. Also, researchers investigated the relationship between climate change and the built environment. Notable examples include Rosenzweig et al. (2011) who analyzed NYC's climate adaptation plan to protect coastal infrastructure, and Hanson et al. (2011) who measured the exposure of major cities to climate change risks.

However, while recognizing adaptation as an integral component (Posas, 2011; Wheeler et al., 2009), research was dominated by mitigation, usually quantitative measurement and control of GHG emissions (Peters, 2009; Scott et al. 2004; Yang et al, 2012), with shipping and ports being no exception (Berechman and Tseng, 2012; Corbett, 2009; Eide et al. 2009; Eide, 2011; Geerlings and van Duin 2011; Psaraftis and Kontovas, 2010; Villalba and Gemechu, 2011). The situation was similar among practitioners. Among the climate change actions plans developed in 34 American states, only 15 included adaptation elements (NRC, 2010b). This was not surprising given the much wider availability of international and bilateral protocols and regulations on mitigation (Keohane and Victor, 2010). Although some relevant studies on adaptation existed, such as Preston et al. (2011) who evaluated 57 climate adaptation plans around the world focusing on the 'quality' of their planning process, while Osthorst and Manz (2012) investigated the changing relationship between stakeholders and surrounding regions while developing climate adaptation strategies in Germany, many were desktop studies based on information as laid down in the adaptation plans which lacked longitudinal investigation on the developmental process. Hence, it is clear there is currently insufficient knowledge, innovation, 'best practices' and local experiences on how to improve the decision-making process in dealing with climate change and its impacts (NRC, 2010a), and this is not helped by the fact that the dynamics between climate change and ports vary significantly between countries. As a consequence, such deficiencies jeopardize port's ability to develop effective adaptation measures, and the results have proven to be tragic (such as Hurricane Sandy's impact on New York City and its port in 2012). In this regard, properly assessing the impact of climate change and its associated risks to ports can be improved considerably when a critical mass in statistical risk data has been developed, but this requires substantial collaborative partnerships between scholars, policymakers and port stakeholders. Such a mismatch largely explains the scarcity of historical, statistical data on the risks posed by climate change to ports (UNCTAD, 2012). All the stated problems imply that without the development of a new analytical model, ports are highly unlikely to improve the quality of adaptation to climate change risks.

2.2 Risk and cost analysis in climate adaptation

It is commonly accepted that climate change, although a naturally occurring process is affected by human activities which may be exacerbating its impact. This leads to a situation where policy responses to climate change have to account for the 'readiness to accept the reality of climate change, institutions and capacity, as well as willingness to embed climate change risk assessment and management in development strategies' (O'Brien et al, 2006). There has been a significant increase in the level of discussion attributable to climate change, for example Wilby et al. (2009), emphasised the need for the 'integration of climate risk information in development planning' across different sectors and countries. Füssel (2007) identified key themes in planning adaptation for climate change where adaptation involves a range of measures to reduce vulnerability, but that adaptation is context specific and needs to consider the climatic, environmental, social and political situation. Further where a decision or adaptation is made in the context of long term policy making climate risk is an important consideration. Policy linkages for climate change responses are also discussed by Schipper and Pelling (2006). Kelly and Adger (2000) discuss the relationship between vulnerability to climate change and the changes necessary for adaptation. Kousky (2014) reviewed papers on 'the potential extent of adaptation in response to changing extreme events'. It was identified that there are significant challenges in estimating the economic costs accruing from climate change and natural disasters. While a number approaches to analysing risks and costs in climate adaptation, O'Brien et al (2006) emphasises the need for new approaches to be developed which can deal with the possible long-term transformations required to accommodate climate change, and the ways in which society responds at all geographical and political levels

Risk analysis for climate change adaptation has been increasingly used, supported by a range of techniques and approaches. Risk assessment decision making frameworks generally consist of risk assessment, option identification, and appraisal of the options before implementation, monitoring and review. Climate change research is an ongoing iterative process and the objective of any analysis is to understand the existing and future risk, estimate the level of risk and determine the level of uncertainty in order to implement realistic adaptation. Techniques to assess risk use both qualitative and quantitative approaches to address the differences between identified climate change adaptation responses (Willows and Connell, 2003; Füssel, 2007; Wilby et al.,2009; Apel et al, 2009; Klinke and Renn, 2002). Issues related to sources of uncertainty, influencing factors, barriers to adaption and enablers of adaptation require qualitative assessment while evaluation of the risks is undertaken using a range of different quantitative assessment approaches. Thus the selection of approaches to be used in a particular situation will vary according to circumstance. Further, the selection of the correct quantitative approach may be challenging depending on the adequacy of the data, the complexity of the problem and potential costs associated with making an incorrect decision. In the academic literature different classifications are used for quantitative approaches to risk analysis in climate adaptation. Wilby et al. (2009) reviewed the various methods and classified them into three approaches: methods requiring limited resources (sensitivity analysis, change factors, climate analogues and trend extrapolation); statistical methods (pattern-scaling, weather generation and empirical downscaling); and techniques requiring significant computing resources (dynamical downscaling and Coupled climate models (ocean – atmosphere/Global Climate Model). Willows and Connell detail both tools and techniques as well as specialised software available for risk assessment and decision analysis related to climate adaptation.

The strategies which could be used in port adaptation measures are likely to be informed by climate adaptation approaches adopted in other fields. Coastal areas face higher probabilities of the risk of disasters and vulnerability due to both natural forcing and the impact of human activity due to the high-energy and rapidly changing environment. The area most closely related to the requirements for port adaptation is thus in the flood and flood risk management context (Aerts, undated; Lehner et al, 2006; Dawson et al, 2009; Edjossan-Sossou et al, 2014; Hattermann et al, 2014; Koks et al., 2015) although other application areas include: landslide (Refice and Capolongo, 2002; Dai et al, 2002); groundwater pollution (Neshat et al, 2015) and drought (Wilhite et al, 2000).

Risk analysis and evaluation techniques related to the costs of damage due to flooding include hydrological models, land use models and economic damage assessments. These allow the integrated analysis of exposure, damage and possible adaptation options (IVM, 2015). Koks et al. (2015) discuss how the effect of policy measures related to risk reduction depends on the ability of the households to adapt and respond to floods. Dawson et al (2009) discuss flooding and erosion risks and how to manage coastal flood and erosion during the next century. Hattermann et al. (2014) analyse possible climate change impacts on flood damage in Germany. Aerts (undated) discusses climate change and the increased probability of flooding in the Netherlands and how this may increase due to the combined effects of sea level rise and increased river discharges. Bagdanavičiute et al (2015) use a multi-criteria evaluation approach to develop and implement a set of indicators of coastal vulnerability.

3. Cost benefit analysis of climate change adaptation measures

Selecting cost effective climate change adaptation measures requires the analysis of the risk reduction as well as the associated costs incurred after the implementation of the measures. The task reveals two major research challenges. One is unavailability of objective data to precisely evaluate the risk reduction and costs, while the other is that risk and costs are expressed by different units and thus, it is difficult to synthesise the evaluated risk and cost results. A preliminary study (Ng et al., 2013) was conducted to address the first challenge by using a discrete fuzzy set approach to model subjective input data (i.e. linguistic terms), leaving the solution to the second to be wanted.

3.1 Fuzzy approach for climate change risk analysis

Many conventional risk assessment approaches (e.g. Quantitative Risk Assessment (QRA)) which have been widely used to carry out risk analysis in many sectors, are not well-suited to deal with climate change risks in which a high level of uncertainties in data exists due to the serious scarcity of historical/statistical data (UNCTAD, 2012). Fuzzy set theory is employed to model linguistic data collected based on subjective judgements (Wang *et al.*, 1996). In this theory, linguistic variables can be characterized by their membership functions to a set of categories, of which they describe the degrees of the linguistic variables. In this project, three parameters closely related to climate change risks are identified based on the Failure Mode and Effect Analysis (FMEA) approach, (Yang *et al.*, 2008; 2009), namely *timeframe (T), likelihood (L)* and *severity of consequences (C)*. The typical linguistic variables and their membership functions for the three risk parameters may be defined with reference to the work by Yang *et al.*, (2008) and characterized as shown in Tables 1-3, in which the linguistics terms are suggested by domain experts through the *Ad Hoc* Expert Meetings organized by the United Nations Conference on Trade and Development (UNCTAD) (Ng et al., 2013).

Table 1. Timeframe

Linguistic terms	**Description**	**Fuzzy numbers**
Very Short (VS)	Less than 1 year	**(0.7, 0.9, 1, 1)**
Short (S)	Approximately 5 years	**(0.5, 0.7, 0.9)**
Medium (M)	Approximately 10 years	**(0.3, 0.5, 0.7)**
Long (L)	Approximately 15 years	**(0.1, 0.3, 0.5)**
Very Long (VL)	More than 20 years	**(0, 0, 0.1, 0.3)**

Table 2. Severity of Consequence

Linguistic terms	**Description**	**Fuzzy numbers**
Catastrophic (CA)	Very severe economic loss and/or disruption on the facilities/systems/services requiring a very long period and very high cost of recovery	**(0.7, 0.9, 1, 1)**
Critical (CR)	Severe economic loss and/or disruption on the facilities/systems/services requiring a long period and long cost of recovery	**(0.5, 0.7, 0.9)**
Major (MA)	Significant economic loss and/or disruption on the facilities/systems/services requiring certain length of time and cost of recovery	**(0.3, 0.5, 0.7)**
Minor (MI)	Some economic loss and/or disruption on the facilities/systems/services requiring some time and cost of recovery	**(0.1, 0.3, 0.5)**
Negligible (NE)	A bit of disruption on the facilities/systems/services, and possibly with some economic loss, but with no real impacts on the continuance of services, nor does it require significant time and cost of recovery	**(0, 0, 0.1, 0.3)**

Table 3. Likelihood

Linguistic terms	**Description**	**Fuzzy numbers**
Very High (VH)	It is very highly likely that the stated effect will occur, with a probability around 90% of at least 1 such incident within the indicated timeframe	**(0.7, 0.9, 1, 1)**
High (H)	It is highly likely that the stated effect will occur, with a probability around 70% of at least 1 such incident within the indicated timeframe	**(0.5, 0.7, 0.9)**
Average (A)	It is likely that the stated effect will occur, with a probability around 50% of at least 1 such incident within the indicated timeframe	**(0.3, 0.5, 0.7)**
Low (L)	It is unlikely that the stated effect will occur, with a probability around 30% of at least 1 such incident within the indicated timeframe	**(0.1, 0.3, 0.5)**
Very Low (VL)	It is very unlikely that the effects will occur, with a probability around 10% of at least 1 such incident within the indicated timeframe	**(0, 0, 0.1, 0.3)**

If T, C and L represent respectively "*Timeframe*", "*Severity of consequence*" and "*Likelihood*", the fuzzy safety score R can be defined by using the following fuzzy set manipulation.

$$R = T \otimes C \otimes L \tag{1}$$

where the symbol "⊗" represents fuzzy multiplication operation in the fuzzy set theory. The membership function of R is thus described by:

$$\mu_R = \mu_T \otimes \mu_C \otimes \mu_L \tag{2}$$

where μ_T, μ_C, and μ_L can be presented by any form of triangular or trapezoidal fuzzy numbers with reference to the defined linguistics variables in Tables 1 – 3. μ_R is a fuzzy number which needs to be defuzzified in order to prioritize the risk level it indicates. A centroid approach (Mizumoto, 1995) may be well suited to modelling the fuzzy expressions of climate risks.

3.2 ER algorithm

The ER approach has been widely used in effectively synthesising pieces of evaluation from various criteria in multi-criteria decision making. In continuously researching and practicing processes, the kernel of this approach, the evidential reasoning algorithm has been developed, improved and modified to achieve greater rationality. The latest algorithm can be analysed and explained in this study by the following pathway.

Let A^k represent the set with five grades[1] (D_1, D_2, D_3, D_4, D_5), which has been synthesised from two subsets $A^{k,+}$ and $A^{k,-}$ associated with $\beta_j^{k,+}$ and $\beta_j^{k,-}$. Then, A, $A^{k,+}$ and $A^{k,-}$ can separately be expressed by (Yang et al., 2013):

$$\begin{aligned}
A^k &= \{\beta_1^k D_1, \beta_2^k D_2, \beta_3^k D_3, \beta_4^k D_4, \beta_5^k D_5\}\\
A^{k,+} &= \{\beta_1^{k,+} D_1, \beta_2^{k,+} D_2, \beta_3^{k,+} D_3, \beta_4^{k,+} D_4, \beta_5^{k,+} D_5\}\\
A^{k,-} &= \{\beta_1^{k,-} D_1, \beta_2^{k,-} D_2, \beta_3^{k,-} D_3, \beta_4^{k,-} D_4, \beta_5^{k,-} D_5\}
\end{aligned} \tag{3}$$

where $\sum_{j=1}^{5} \beta_j^k$, $\sum_{j=1}^{5} \beta_j^{k,+}$ and $\sum_{j=1}^{5} \beta_j^{k,-}$ equal 1.

Suppose $\theta^{k,+}$ and $\theta^{k,-}$ represent the normalised $w^{k,+}$ and $w^{k,-}$, and $\theta^{k,+} + \theta^{k,-} = 1$. Suppose M_j^{k+} and $M_j^{k,-}$ ($j = 1, 2, 3, 4, 5$) are individual degrees to which the subsets $A^{k,+}$ and $A^{k,-}$ support the hypothesis that the synthesised evaluation is confirmed to the four control modes. Then, M_j^{k+} and $M_j^{k,-}$ can be obtained as follows:

$$M_j^{k,+} = \theta^{k,+} \times \beta_j^{k,+} \qquad M_j^{k,-} = \theta^{k,-} \times \beta_j^{k,-} \tag{4}$$

Suppose ${\beta_j^k}'$ ($j = 1, 2, 3, 4, 5$) represents the non-normalized degree to which the synthesised evaluation is confirmed to the five grades as a result of the synthesis of the

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[1] Five grades are selected for a demonstrative purpose. The ER approach can accommodate infinite grades in theory.

conditional belief degrees in the subsets $A^{k,+}$ and $A^{k,-}$. Suppose $H_U{}'$ represents the non-normalized remaining belief unassigned after the commitment of belief to the four grades as a result of the synthesis of $A^{k,+}$ and $A^{k,-}$. The evidential reasoning algorithm (Yang and Xu, 2002) can be stated as follows:

$$\beta_j^{k'} = K\ (M_j^{k,+} \times M_j^{k,-} + M_j^{k,+} \times \theta^{k,+} + \theta^{k,-} \times M_j^{k,-})$$

$$H_U{}' = K\ (\theta^{k,-} \times \theta^{k,+})$$

$$K = [1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} M_T^{k,+} M_R^{k,-}]^{-1} \tag{5}$$

After the above aggregation, the combined degrees of belief β_j^k are generated by assigning $H_U{}'$ back to the four control modes using the following normalization process:

$$\beta_j^k = \beta_j^{k'} / (1 - H_U{}')\ (j = 1, 2, 3, 4, 5) \tag{6}$$

The above calculation process has been computerised by the evidential reasoning software IDS (Yang and Xu, 2002). Although showing attractiveness, the ER approach still reveals practical problems in its real applications. As indicated in Eq (5), the two subsets need to be expressed on the same utility universe, which can be measured in terms of five cost effectiveness expressions in Table 4 (i.e. "*Very Effective*", "*Effective*", "*Average*", "*Slightly Effective*" and "*Ineffective*") in order to have the ER applied for the synthesis. However, in the cost effectiveness evaluation of adaptation measures, risk reduction will be expressed by a crisp value (quantitative data), which is obtained by the difference between two defuzzified risk index values in Section 3.1, while the cost evaluations will be largely conducted by domain experts using linguistic terms (i.e. qualitative data). To facilitate the synthesis, both quantitative and qualitative data are transformed into the same scale defined by the five cost effectiveness expressions as follows.

Table 4. Cost effectiveness of adaptation measures

Linguistic terms	**Fuzzy numbers**
Very effective (VE)	**(0.7, 0.9, 1, 1)**
Effective (E)	**(0.5, 0.7, 0.9)**
Average (A)	**(0.3, 0.5, 0.7)**
Slightly effective (SE)	**(0.1, 0.3, 0.5)**
Ineffective (I)	**(0, 0, 0.1, 0.3)**

3.2.1 Risk reduction modelling - quantitative data transformation

In Section 3.1, the risk index value of the i^{th} climate threat can be obtained and expressed as $P_{S(R_i)}$. Suppose j^{th} adaptation measure is implemented to reduce the risk level of the i^{th} threat. Updated input with respect to *T, L* and *S* will be used to calculate a new risk index value $P^j_{S(R_i)}$ after the implementation of the j^{th} measure. Consequently, the risk reduction of the i^{th} climate threat by the j^{th} adaptation measure can be obtained as follows.

$$RR_i^j = P_{S(R_i)} - P^j_{S(R_i)} \tag{7}$$

To map the numerical RR_i^j onto the five defined cost effectiveness expressions, five risk reduction grades are defined as $\{RG^1, RG^2, RG^3, RG^4, RG^5\}$ and calculated as follows, respectively.

$$RG^1 = \max\{RR_i^j\}$$
$$RG^2 = \frac{RG^1 + RG^3}{2} = \frac{3\max\{RR_i^j\} + \min\{RR_i^j\}}{4}$$
$$RG^3 = \frac{RG^1 + RG^5}{2} = \frac{\max\{RR_i^j\} + \min\{RR_i^j\}}{2}$$
$$RG^4 = \frac{RG^3 + RG^5}{2} = \frac{\max\{RR_i^j\} + 3\min\{RR_i^j\}}{4}$$
$$RG^5 = \min\{RR_i^j\} \tag{8}$$

Consequently, RR_i^j can be expressed by RG^k ($k=1, 2, ..., 5$) when $RR_i^j = RG^k$. When $RR_i^j \neq RG^k$, RR_i^j belongs to RG^k with a belief degree of $\frac{RG^{k+1} - RR_i^j}{RG^{k+1} - RG^k}$ and RR_i^j belongs to RG^{k+1} with a belief degree of $\frac{RR_i^j - RG^k}{RG^{k+1} - RG^k}$. (9)

When an adaptation measure contributes to the maximal risk reduction (i.e. *RG1*), it is considered to be "Very effective" in the utility universe as far as risk factor is concerned. Similarly, when risk reduction is RG^2, RG^3, RG^4 or RG^5, the adaptation measure is "Effective", "Average", "Slightly effective" or "Ineffective", respectively.

3.2.2 Cost modelling - qualitative data transformation

Generally, risk reduction and cost are two conflicting objectives, with higher risk reduction leading to higher costs. This means that if the risk reduction associated with an adaptation measure is improved, higher costs will usually be incurred. The cost incurred for the risk reduction associated with an adaptation measure is usually affected by many factors, including the investment of a new system and cost of labour incurred in redesign of the system if necessary to meet some unexpected needs at the initial stage, etc. Such factors are of large uncertainties, largely subject to the implementation of new adaptation measures. In an early design stage, it can be very difficult to assess the factors in quantitative forms. With the fuzzy approach in risk estimation, it is not surprising that safety engineers often prefer to estimate costs incurred in risk reduction using linguistics variables (Wang et al., 2006). The cost incurred for adaptation measures can be described using linguistic variables such as *{"Very high", "High", "Average", "Low", "Very low"}.* Such linguistic variables can also be described, as shown in Table 5, in terms of membership values.

Table 5. Fuzzy numbers of cost expressions

Linguistic terms	Fuzzy numbers
Very low (VL)	**(0.7, 0.9, 1, 1)**
Low (L)	**(0.5, 0.7, 0.9)**
Average (A)	**(0.3, 0.5, 0.7)**
High (H)	**(0.1, 0.3, 0.5)**
Very high (VH)	**(0, 0, 0.1, 0.3)**

From Tables 4 and 5, the cost expressions and the utility expressions are defined by the same membership functions, cost descriptions can be directly mapped onto the cost effectiveness utility universe as follows. When the cost is "Very low", the adaptation measure is "Very efficient" as far as the cost factor is concerned. Similarly, when the cost is "Low", "Average", "High" or "Very high", the adaptation measure is *"Effective"*, *"Average"*, *"Slightly effective"* and *"Ineffective*", respectively.

Having mapped the risk and cost factors on the utility universe, the ER approach can be used to synthesise the risk reduction and cost evaluations of the j^{th} adaptation measure with respect to the i^{th} climate threat to obtain its cost effectiveness result as follows.

$$CE_{i,j} = \{(\beta^1_{i,j}, \text{“}\textit{Very effective}\text{”}), (\beta^2_{i,j}, \text{“}\textit{Effective}\text{”}), (\beta^3_{i,j}, \text{“}\textit{Average}\text{”}), (\beta^4_{i,j}, \text{“}\textit{Slightly effective}\text{”}), (\beta^5_{i,j}, \text{“}\textit{Ineffective}\text{”})\}$$

To select the most cost effective adaptation measure, it is necessary to describe the five utility expressions using numerical values. Using centroid defuzzification method (Mizumoto, 1995), the crisp values of the five utility expressions in Table 4 are obtained as (0.892, 0.7, 0.5, 0.3, 0.108).

Naturally, a numerical cost effectiveness index of an adaptation measure can be obtained by the following calculation:

$$I(CE_{i,j}) = \beta^1_{i,j} \times 0.892 + \beta^2_{i,j} \times 0.7 + \beta^3_{i,j} \times 0.5 + \beta^4_{i,j} \times 0.3 + \beta^5_{i,j} \times 0.108 \quad (10)$$

Consequently, the higher $I(CE_{i,j})$ *is*, the better the adaptation measure.

4. Case study – cost benefit analysis of adaptation measure: a pilot study of a North American port

To demonstrate the feasibility of the developed cost benefit analysis model, a pilot study based on a North American port (hereinafter called 'the Port') was investigated.[2] Necessary data was collected through a pioneer questionnaire survey in Table 6 (Yang et al, 2015), duly completed by three maritime stakeholders from the Port in the fall of 2012. They included a senior official from the Port, a senior official from a health and environmental group and a senior consultant appointed to develop the Port's adaptation plan (mainly done between 2010 and 2012). They, as the key decision makers, represented the major groups who were involved in climate adaptation planning in the Port. Simultaneously, they also possessed diversified interests and perception about how ports

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[2] The identity of the port is not released due to confidentiality considerations and the sensitive nature of the topic.

should adapt to climate change and its impacts. The data are categorised in three groups, risk evaluation without the implementation of adaptation measures, risk evaluation with the implementation of adaptation measures, cost evaluation of the adaptation measures.

Based on the discrete fuzzy approach in Section 3.1 and the work (Ng et al., 2013), the risk results of each potential threat (PT) of environmental driver (ED) on the Port with and without the adaptation measures are calculated and expressed in Table 6, respectively. For instance, with the adaptation measure “Move facilities out of harm's way”, the evaluations of the three risk parameters of the PT “High waves that can damage the Port’s facilities” due to the ED “Sea level rise” from the three experts are “Very long”, “Very long” and “Very long” for the timeframe (T), “Negligible”, “Major” and “Minor” for the severity of consequence (S) and “Low”, “Average” and “Average” for the likelihood (L), respectively. Averaging the three experts’ judgements enables to obtain the fuzzy risk input data with respect to the three parameters, T, S and L as follows.

T = (0, 0, 0.1, 0.3)
S = (0.133, 0.267, 0.3, 0.5)
L = (0.233, 0.433, 0.633)

Using Eq (2), the risk result is calculated as
$\mu_R = \mu_T \otimes \mu_C \otimes \mu_L = (0, 0, 0.013, 0.095)$.

Using the centroid defuzzificaiton method, $\mu_R = 0.032$

Table 6. Questionnaire results with respect to risk and cost analysis

Environmental driver (ED) due to climate change	Potential threat (PT) of ED on the Port	Adaptation measure to address the potential threat of ED on the Port	Risk result without adaptation measures	Risk result with adaptation measures	Risk reduction (RR_i^j)	Cost
Sea level rise	High waves that can damage the Port’s facilities	Move facilities	0.146	0.032	0.114	33% H, 67%VH
		Build new breakwaters	0.146	0.06	0.086	33% H, 67%VH
		Increase breakwater dimensions	0.146	0.063	0.083	33% L, 33% H, 33% VH
	Port installations (like cranes and warehouses) in the Port get flooded	Raise port elevation	0.088	0.044	0.044	33% H, 67%VH
	Transport infra- and superstructures in the Port get flooded	Improve transport infra- and superstructures resilience to flooding	0.135	0.063	0.072	33% A, 33% H, 33% VH
	Coastal erosion at or adjacent to the Port	Protect coastline and increase and beach nourishment programs	0.185	0.102	0.083	67% A, 33% H

	Deposition and sedimentation along the Port’s channels	Increase and/or expand dredging	0.148	0.074	0.074	100% H
Storm surge intensity and/or frequency	Waves that can damage the Port’s facilities	Move facilities	0.216	0.041	0.175	33% H, 67%VH
		Build new breakwaters	0.216	0.096	0.12	33% H, 67%VH
		Increase breakwater dimensions	0.216	0.079	0.137	33% A, 33% H, 33% VH
	Flooding within the Port due to storm surge	Raise port levels, move facilities, build coastal defences	0.310	0.051	0.259	33% H, 67%VH
	Downtime in the Port operation due to high winds	Increase port size to deal with bottlenecks	0.163	0.069	0.094	33% VL, 33% A, 33% H
	High wind damage to port installations (like cranes and warehouses) in the Port	Increase the future standards of the Port’s construction to deal with higher winds	0.191	0.071	0.12	100% L
	Coastal erosion at or adjacent to the Port	Expand beach nourishment programs	0.265	0.127	0.138	67% A, 33% H
	Deposition and sedimentation along the Port’s channels	Increase and/or dredging	0.199	0.109	0.09	100% H
Changing quality and quantity of agricultural and seafood production	Reduce the competitiveness of the Port dedicated to such products	Enhance communication between the Port and surrounding regions, and encourage more inputs from surrounding regions on climate adaptation	0.064	0.043	0.021	67% L, 33% A
	Negatively affect the economic well-being of surrounding communities which largely depend on the Port	The Port acts as the ‘network manager’ to liaise with all related stakeholders and coordinate adaptation plans and strategies (both inside and outside port areas)	0.072	N/A	N/A	100% L

In Table 6, it is seen that the max(RR_i^j) = 0.259, while the min(RR_i^j) = 0.021. Given Eq. (8), RG^k ($k=1, 2, \ldots, 5$) = (0.259, 0.2, 0.14, 0.085, 0.021).

As a result, all the obtained RR_i^j in Table 6 can be transformed and presented by the utility linguistics expressions defined in Table 4. For example, RR_1^1 = 0.114, which is a value between RG^3 (=0.14) and RG^4 (=0.085). By using Eq. (9), it can be calculated and presented as 52.7% RG^3 (Average) and 47.3% RG^4 (Slightly effective). In a similar way, each RR_i^j can be transformed and expressed by RG^k in Table 7.

Table 7. Transformed results of risk reduction and cost analysis by using utility expressions

Environmental driver (ED) due to climate change	**Potential threat (PT) of ED on the Port**	**Adaptation measure to address the potential threat of ED on the Port**	**Utility expressions of risk reduction (RR_i^j)**	**Utility expressions of cost analysis**
Sea level rise	High waves that can damage the Port's facilities	Move facilities	52.7% A, 47.3% SE	33% SE, 67% I
		Build new breakwaters	1.8% A, 98.2% SE	33% SE, 67% I
		Increase breakwater dimensions	96.7% SE, 3.3% I	33% E, 33% SE, 33% I
	Port installations (like cranes and warehouses) in the Port get flooded	Raise port elevation	35.9% SE, 64.1% I	33% SE, 67% I
	Transport infra- and superstructures in the Port get flooded	Improve transport infra- and superstructures resilience to flooding	79.7% SE, 20.3% I	33% A, 33% SE, 33% I
	Coastal erosion at or adjacent to the Port	Protect coastline and increase and beach nourishment programs	96.7% SE, 3.3% I	67% A, 33% SE
	Deposition and sedimentation along the Port's channels	Increase and/or expand dredging	82.8% SE, 17.2% I	100% SE
Storm surge intensity and/or frequency	Waves that can damage the Port's facilities	Move facilities	58.3% E, 41.7% A	33% SE, 67% I
		Build new breakwaters	63.6% A, 36.4% SE	33% SE, 67% I
		Increase breakwater dimensions	94.5% A, 5.5% SE	33% A, 33% SE, 33% I
	Flooding within the Port due to storm surge	Raise port levels, move facilities, build coastal defences	100% VE	33% SE, 67% I
	Downtime in the Port's operation due to high winds	Increase port size to deal with bottlenecks	16.4% A, 83.6% SE	33% VE, 33% A, 33% SE
	High wind damage to port installations (like cranes and warehouses) in the Port	Increase the future standards of the Port's construction to deal with higher winds	63.6% A, 36.4% SE	100% VE
	Coastal erosion at or adjacent to the Port	Expand beach nourishment programs	96.4% A, 3.6% SE	67% A, 33% SE

	Deposition and sedimentation along the Port's channels	Increase and/or dredging	9.1% A, 90.9% SE	100% SE
Changing quality and quantity of agricultural and seafood production	Reduce the competitiveness of the Port dedicated to such products	Enhance communication between the Port and surrounding regions, and encourage more inputs from surrounding regions on climate adaptation	100% I.	67% E, 33% A
	Negatively affect the economic well-being of surrounding communities which largely depend on the Port	The Port acts as the 'network manager' to liaise with all related stakeholders and coordinate adaptation plans and strategies (both inside and outside port areas)	Between 100% I and (79.2% SE, 20.8% I)[3]	100% E

Next, the ER algorithm (Eqs (3)-(6)) and its associated computing software package IDS are used to synthesise the risk reduction and cost analysis input for conducting the cost benefit analysis of each adaptation measure. Assume that the importance of risk reduction and cost is the same. The synthesis result for the measure "Moving facilities" addressing the PT "High wavers" by the driver "Sea level rise" is calculated as follows. It is also shown in Figure 1.

$CE_{1,1}$ = {(0, "*Very effective*"), (0, "*Effective*"), (24.44%, "*Average*"), (44.48%, "*Slightly effective*"), (31.07%, "*Ineffective*")}

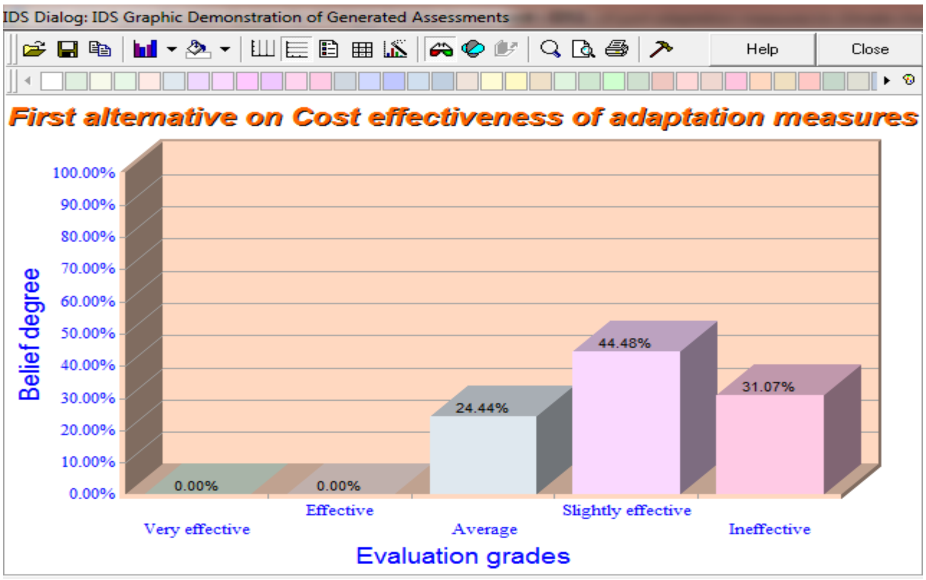

Figure 1. The cost effectiveness result of adaptation measure "Moving facilities"

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[3] If it is the best case in which the risk is totally eliminated with the implementation of the measure, then the risk reduction is 0.072, which can be transformed 79.2% SE, 20.8% I. If it is the worst case, the measure is 100% Ineffective.

Using Eq (10), the cost effectiveness index of the adaptation measure is obtained by the following calculation:

$$I(CE_{1,1}) = 0\times0.892+0\times0.7+0.2444\times0.5+0.4448\times0.3+0.3107\times0.108 = 0.2892$$

Similarly, the cost effectiveness index of each adaptation measure is obtained in Table 8.

Table 8. Cost effectiveness of adaptation measures

Environmental driver (ED) due to climate change	Potential threat (PT) of ED on the Port	Adaptation measure to address the potential threat of ED on the Port	Cost effectiveness index of adaptation measures
Sea level rise	High waves that can damage the Port's facilities	Move facilities	0.2892
		Build new breakwaters	0.2462
		Increase breakwater dimensions	0.3250
	Port installations (like cranes and warehouses) in the Port get flooded	Raise port elevation	0.1688
	Transport infra- and superstructures in the Port get flooded	Improve transport infra- and superstructures resilience to flooding	0.2789
	Coastal erosion at or adjacent to the Port	Protect coastline and increase and beach nourishment programs	0.3550
	Deposition and sedimentation along the Port's channels	Increase and/or expand dredging	0.2883
Storm surge intensity and/or frequency	Waves that can damage the Port's facilities	Move facilities	0.3940
		Build new breakwaters	0.2993
		Increase breakwater dimensions	0.4090
	Flooding within the Port due to storm surge	Raise port levels, move facilities, build coastal defences	0.5317
	Downtime in the Port operation due to high winds	Increase port size to deal with bottlenecks	0.4319
	High wind damage to port installations (like cranes and warehouses) in the Port	Increase the future standards of the Port's construction to deal with higher winds	0.6596
	Coastal erosion at or adjacent to the Port	Expand beach nourishment programs	0.4719
	Deposition and sedimentation along the Port's channels	Increase and/or dredging	0.3063

Changing quality and quantity of agricultural and seafood production	Reduce the competitiveness of the Port dedicated to such products	Enhance communication between the Port and surrounding regions, and encourage more inputs from surrounding regions on climate adaptation	0.3710
	Negatively affect the economic well-being of surrounding communities which largely depend on the Port	The Port acts as the 'network manager' to liaise with all related stakeholders and coordinate adaptation plans and strategies (both inside and outside port areas)	0.4420 (averaging 0.4040 and 0.4800)

From the analysis results in Table 8, the most cost effective adaptation measure is "Increase the future standards of the Port's construction to deal with higher winds" to address the PT "High wind damage to port installations (like cranes and warehouses) in the Port" due to the climate driver "Storm surge intensity and/or frequency". It is followed by the measures "Raise port levels, move facilities, build coastal defences" and "Expand beach nourishment programs" in sequence.

6. Conclusion

Climate change adaptation is a key topic and element of sustainable management in any area of the economy. In the particular case of ports, climate change is likely to impact on the operations of ports as well as on strategic development and extension of ports. The findings indicate that the application of climate change adaptation measures recommended in the literature can bring a considerable overall reduction of the risks of the likely climate change events affecting the operations of ports. The research found that the main climate change threats to port operations are high waves damaging port facilities, flooding at port due to extreme storms, damages caused by high winds and coastal erosion. Although the effectiveness of range of climate change adaptation port-related measures was evaluated in the research and the results of the modelling highlight that climate change adaptation can be a solution for achieving continuity of port operation under extreme weather conditions, there are a wide range of climate change adaptation measures which could adopted by ports and each port needs to prioritise based on the likelihood and expected severity of climate change events as well as the investment funds available to ports.

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