Climate change adaptation for seaports and airports

Mark Ching-Pong Poo

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Abbreviations

ABC	Artificial bee colony
ABZ	Aberdeen International Airport
AHP	Analytic Hierarchy Process
BDI	Baltic Dry Index
BHX	Birmingham Airport
BODC	British Oceanographic Data Centre
CAA	Civil Aviation Authority
CCRI	Climate change risk indicator
CCVI	Climate change vulnerability index
CIA	Climate impact assessment
ConI	Consistency Index
ConR	Consistency Rate
CR	Risk of a territory being affected by climate change
CRI	Climate resilience indicator
CTOS	Container terminal operations simulator
CVI	Coastal vulnerability indices
CVPR	Capacitated vehicle routing problem
CWL	Cardiff Airport
DEM	Digital elevation model
DEFRA	Department for Environment, Food and Rural Affairs
DfT	Department of Transport
DOB	Degree of belief
DOV	Dover
DSS	Decision support system
DUN	Dundee
EA	Environment Agency

EDI	Edinburgh Airport
EMA	East Midlands Airport
EM-DAT	Emergency Events Database
EUROCONTROL	The European Organisation for the Safety of Air Navigation
EWE	Extreme weather event
FEL	Felixstowe
FER	Fuzzy evidence reasoning
GDP	Gross domestic product
GHG	Green house gases
GLA	Glasgow Airport
GIS	Geographic information system
GRA	Grangemouth
GSN	Global shipping network
GVA	Gross value added
HAZMAT	Hazardous materials
HM Government	Her Majesty's Government
HM Land Registry	Her Majesty's Land Registry
IDF	Intensity–duration–frequency
IDS	Intelligent decision system
IMM	Immingham
IPCC	Intergovernmental Panel on Climate Change
LEI	Leigh
LGW	Gatwick Airport
LHR	Heathrow Airport
LIV	Liverpool
LON	London
LTN	London Luton Airport

MAN	Manchester Airport
Met Office	Meteorological Office
MIH	Milford Haven
MOO	Multiple-objective optimisation
NHF	National housing federation
NOC	National Oceanography Centre
OD	Origin-destination
OECD	The Organisation for Economic Co-operation and Development
RI	Ratio Index
SCM	Supply chain management
SHE	Sheerness
SI	Swarm intelligence
SR	Saturation rate
SLR	Sea-level rise
SOU	Southampton
STN	London Stansted Airport
TEE	Tees
TT-DEWCE	Task Team on Definitions of Extreme Weather and Climate Events
UK	United Kingdoms
UK AIR	UK Air Information Resources
UNCTAD	United Nations Conference on Trade and Development
VRP	Vehicle routing problem
WMO	World Meteorological Organization

Publications arising from this work

<u>Journal article</u>

Ching Pong Poo; Zaili Yang. (2020) Assessing the climate resilience of the global shipping network by an optimisation model. [Unassigned]

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Ching Pong Poo; Zaili Yang; Delia Dimitriu; Zhuohua Qu. (2018) Review on seaport and airport adaptation to climate change: a case on sea level rise and flooding. Maritime Technology Society Journal.

<u>Conference Proceeding</u>

Ching Pong Poo; Zaili Yang; Delia Dimitriu; Zhuohua Qu. (2020) Climate change adaptation for seaports by Climate resilience indicator (CRI) framework. the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference, June 21–26, 2020, Venice, Italy

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Abstract

Seaports and airport systems, being crucial nodes in international supply chains with high similar operational functions, are highly vulnerable to the risks that climate change poses to their infrastructure and operations. Transportation systems' inability to adapt to climate change risk would result in a severe blow to economic prosperity and human welfare. It is now too late to avoid all harmful effects posed by climate change, not least due to the uncertainties on how they should be addressed. Policymakers and stakeholders must thoroughly understand potential climate change risks on seaports and airports, and undertake appropriate adaptation planning and strategies to tackle them. However, until now, there are inadequate works on reducing the uncertainties of decision-making when dealing with climate change and its impacts on human welfare.

With the occurrence of increasingly frequent and severe climate-related events, adapting to the impacts posed by climate change has been a pivotal research topic influencing transport operation, infrastructure, planning and policymaking in recent decades. As most studies on climate change still focus on its short-term impacts, there is insufficient research on how to systematically adapt to the effects of climate change on transportation, in particular in the critical nodes of transport system, e.g., seaports and airports. Hence, it urgently requires illustrating the status quo regarding long-term risks posed by climate change on seaports and airports, including detailed analyses of the current measures and dilemmas in handling the issues of climate change and adaptation of planning to provide competent advice with seaport and airport stakeholders.

Over the past few years, the focus on climate change study has switched from just mitigation to both mitigation and adaptation. As global warming is still unstoppable, and it brings more extreme weather, accidents and failures become more frequent. Moreover, losses and fatalities are more severe. In the past two decades, several weather-related severe events have caused significant economic loss. In 2005, Hurricane Katrina in the United States was one of the deadliest hurricanes (CNN, 2017b). In 2011, Tohoku, Japan, a Tsunami destroyed several provinces (CNN, 2017a). It brought more than 15,000 deaths, and about 230,000 people lost their homes. In 2011, Missouri experienced the deadliest U.S. tornadoes, which killed 161 people (Wheatley, 2013). In 2012, Louisiana, Mississippi, Alabama and Arkansas faced an intense and rainy Hurricane Issac which cost $2.0 billion regarding insured loss and left more than 644,000 people without power (Castellano et al., 2012). In 2013, a two mile-tornado near

Oklahoma City caused more than 50 deaths and destroyed many homes (Howell et al., 2013). During the 2017 Atlantic hurricane season, more than nine hurricanes threatened North America and Caribbean areas. Until October, storms, including the most potent Maria, brought more than 200 billion dollars in losses and 103 death toll in the U.S. (Vo and Castro, 2018). For instance, in 2018, Typhoon Mangkhut crashed into Asian countries by bringing high winds and storm surges to the coastal cities. Transportation is profoundly affected by extreme weather (Wallemacq et al., 2018). Seaports are the critical nodes of international supply chains and thus stand on the edge of social and economic disasters.

Besides storms and flooding, the heatwave also presents a severe climate issue. In 2003, the heatwave in Central Europe caused the death toll of more than 70,000 (Bouchama, 2004). On the other hand, extreme and continuous heat can also damage road surfaces and distort rail lines (Sieber, 2013), and it affects the land transport connectivity of seaports. Apart from the heatwave, fog disrupts transportation services across the United Kingdoms (UK) (World Market Intelligence News, 2015). Therefore, climate change adaptation planning for seaports and airports is critical to visualise the climate risks of passengers and goods from different extreme weather events (EWEs). As the seaports and airports are hubs in the global network, climate impacts can be assessed locally and internationally. So, this thesis presents five main working packages for evaluating the climate impact with different perspectives.

The Intergovernmental Panel on Climate Change (IPCC) is an international body for assessing the science related to climate change. Climate change adaptation is one of the critical studies by the IPCC working group II in the fifth Assessment Report (IPCC, 2014a). IPCC has undertaken thorough reviews on transport infrastructures and stated that transportation systems would face enormous challenges by the environment in the near future (2030-2040) and the long future (2080-2100), especially in developed cities. They have also indicated climate-related drivers of impacts for coastal zone systems and transportation systems. Coastal cities with extensive port facilities and large-scale industries are vulnerable to increased flood exposure. High-growth cities located in low-lying coastal areas are also at higher risk. There is a possibility of a nonlinear increase in coastal vulnerability over the next two decades. Especially in developed country cities, climate change also leads to potentially significant secondary economic impacts with regional and possibly global consequences for trade and business. Emergency response requires well-functioning transport infrastructure. Furthermore, IPCC finds that a changing climate leads to changes in EWEs in different sectors, including frequency, intensity, spatial extent, duration, and timing. It can result in unprecedented extreme weather and climate events (IPCC, 2012).

Starting with an extensive literature review, this thesis proposes the five main research themes regarding academic journals on seaport and airport adaptation to climate change, addresses on climate change from international organisations, climate change adaptation reports in the United Kingdom, centrality assessment in maritime transportation, port disruption due to climate extremes, multiple-objective decision support for environmental sustainability in maritime industry, and Artificial Bee Colony (ABC) algorithm for vehicle routing problem and supply chain management. Literature shows that existing research on climate change is relatively scattered, lacking in leading journals, researchers and theories. Especially, climate adaptation planning is still at an embryonic stage that even transport planners who have taken countermeasures to minimise the impacts of climate change confront a few dilemmas remaining. Also, climate vulnerability assessments are still at a national and regional level, and the climate change impact on the global shipping network (GSN) has not been assessed yet. Based on the review, there are two focuses for the upcoming parts of the thesis, regional study and international study.

The first part of the regional study is to explore a standardised conceptual framework for developing a Climate change risk indicator (CCRI) framework for climate adaptation of transportation critical infrastructures, including seaports and airports. The assessments by implying the CCRI framework enables research-informed policymaking on such a demanding and multi-discipline topic. Many climate assessments have been done for measuring climate vulnerabilities, and various climate adaptation measures have been proposed for reducing climate risks. However, few of them used quantitative approaches for climate risk evaluations in seaports and airports, and fewer on the provisions of CCRIs for comparing climate risks of different locations. Furthermore, climate change is a dynamic issue, requiring big objective data to support the analysis (e.g. monthly climate data on CCRIs) of climate threats and vulnerabilities. In this part, Fuzzy Evidence Reasoning (FER) is employed to evaluate the climate risks in seaports and airports because incomplete forecasting data are in place. The findings reveal that climate change risks are varied in different locations and different months. Nevertheless, the risk levels of seaports and airports in the future are assessed for observing the changes and informing policymaking.

By integrating the CCRI framework with an expert-supported seaport vulnerability indicator framework in the North East United States, a Climate resilience indicator (CRI) framework is designed to access the climate resilience level by assessing the indicators on exposure, sensitivity, and adaptive capacity. The conceptual framework is then constructed by a nationwide survey among the seaport and airport stakeholders in the UK. It also illustrates an overall picture of current climate adaptation issues in both the seaport and airport domains by weighting the indicators in the framework.

Then, the further comparative analysis takes place by comparing the results of both seaports and airports by the CCRI and CRI frameworks. Also, climate change adaptation reports of seaports and airports of the UK and peer-reviewed works of literature related to climate change adaptation are collected and summarised to present the differences between seaports and airports on climate adaptation issues.

On the international side, the climate vulnerability of the whole shipping network is assessed by combining two assessments, centrality assessment and ship routing assessments. First, a centrality assessment of port cities by a novel multi-centrality-based indicator is implemented. Afterwards, the centrality assessment result has been used to analyse global climate vulnerabilities by a set of climate vulnerability and adaptation indices. These reveal that climate vulnerabilities are needed to be tackled within a "node" (seaport) and in the whole seaport network. Then, a shipping network model has been designed to find the optimum shipping route between ports, and changes in route selections based upon more port disruption days caused by extreme weather. The Artificial bee colony (ABC) algorithm, an optimisation algorithm based on the intelligent foraging behaviour of a bee swarm, is imparted in the model. The central ports, known as hubs, are found in the centrality assessment, are exclusively tested on changes to look at the sensitivity on shipping networks between continents. The routing problem is somewhat simpler for airports than seaports as the short-haul is under three hours, the medium-haul is three to six hours, long haul is six to twelve hours, and ultra-long-haul is over twelve hours. Comparing ultra-long-haul with more than 30 days for seaports, it is not necessary to implement the airline data to the routing model as the decision of flying is relatively binary. Therefore, airport network is dropped for network assessment.

This research re-emphasises the importance of raising the awareness of the community's consideration of the risks of climate change on seaports and airports and strives for useful risk analysis and adaptation planning to cope with them. Findings from this thesis show that the newly developed climate adaptation framework, together with the FER model and empirical case studies, has provided a pioneer trail in systematically evaluating climate risks in the whole British transport system. This work has great potential to be tailored for broader applications, offering useful recommendations and global references for climate adaptation in other regions. On the other hand, the international shipping network is assessed by a vessel routing model, together with centrality assessment and climate vulnerability index. This work has great potential to be tailored for more comprehensive assessments, offering global references for climate adaptation in other transportation systems, especially airports.

Chapter 1 Introduction

1.1. Summary

This chapter briefly introduces the research background and sets the scene for the thesis by presenting its research questions, research objectives, scope, the context of each chapter, and thesis structure.

1.2. Research Background

Maritime transport is the backbone of international trading (UNCTAD, 2018). Nowadays, over 80% of merchandise trade in the world by volume is delivered on the sea (Yip et al., 2011). Containers take an essential role in reducing damage and leading to higher productivity during handling phases (Vojdani et al., 2013). Since 1990, container trade, which is counted in terms of twenty-foot equivalent units (TEUs), is estimated to have had a drastic fivefold increase. The industry is still expanding by the increase of infrastructure and the trading demand (Liu et al., 2013, Yip and Wong, 2015). On the other hand, air cargo plays a significant role in ensuring aviation is the "business of freedom". Enabling global trade stimulates economic growth and promotes a better quality of life for all people in every part of the planet, irrespective of them ever boarding a plane. Airfreight demand ended 2018 up 3.4%, despite softening late in the year, and Freight capacity was up 5.4%, outpacing annual demand growth, but yields remained robust (IATA, 2019). Human activities and populations, including shipping and aviation, are rapidly changing both positively and negatively the earth system and its components at local, regional, and global scales. Greenhouse gas emissions continue to increase in most regions (Leemans and Solecki, 2013).

Globally, the awareness of climate change and urbanisation is growing, as their consequences become increasingly apparent. 40% of the global population lives within 100 km of the coast, and port cities are significant concentrations for a population with 13 out of the 20 most populated cities in the world in 2005 being port cities. Extreme weather events, supercharged by climate change, affected some 62 million people around the world in 2018 (United Nations, 2019). Highly populated port cities, with seaports and usually airports, are in areas vulnerable to climate change impacts: on coasts susceptible to sea-level rise and storms or at mouths of rivers susceptible to flooding (Becker et al., 2012). In the past few years, there has been a growing interest among researchers and practitioners to reduce the carbon footprint of maritime shipping and aviation logistics for mitigating climate change effect by adopting operations management practices. These include operational decisions such as speed reduction, berth scheduling and route re-engineering to rationalise fuel consumption and to reduce CO2 emissions. On the adaptation direction, there is growing interest but mainly focusing on climate vulnerability assessments and risk assessments (Poo et al., 2018b) and yet to implement operations management practices. For airports, operational management study is more popular, but only to undergo a climate vulnerability assessment.

A pure climate study on transportation systems would be of questionable value without a greater understanding of the potential future sensitivity of the sector (Jaroszweski et al., 2010). Studies in climate change adaptation, in general, exist to provide new insights to the policymakers and intuitional decision-makers. However, decision-making models capable of climate vulnerability for adaptation resource allocation is under development. There was insufficient work on the adaptation modelling work based on multiple attributes (Yang et al., 2018) to provide empirical evidence on significant aids to climate adaptation policymaking. As there are different climate threats influencing the transport infrastructure, a platform to integrate all climate vulnerabilities is essential to assess the climate vulnerabilities of transport infrastructures (e.g. seaports and airports) in different seasons, and now and in future. Setting up an assessment framework is a suitable method to tackle this issue. Also, the resources for climate change adaptation can be scientifically allocated for different seaports and airports against different climate threats in different seasons. Also, it is crucial to integrate all climate threats to compare the climate vulnerabilities across seaports by this multi-port platform, and thus to implement suitable adaptation measures to a particular seaport and airport (Zommers and Alverson, 2018).

Coastal cities are also exposed to the risk of the impacts of climate variability and change, particularly given their location in coastal zones, low-lying areas and deltas. EWEs can cause failures in different parts of cities, and the global transportation network may suffer a cascading breakdown. Therefore, climate vulnerability assessments are not enough just focusing on seaports and airports, known as nodes, independently. Also, a network vulnerability study for a global logistics system is needed to test the network resilience against failures in different seaports (Berle et al., 2011, Gonzalez Laxe et al., 2012).

The climate impacts on the UK can be assessed on an international disasters database called Emergency Events Database (EM-DAT), which is a free open online database that containing worldwide data (Guha-Sapir et al., 2015). The data include the occurrence, type, and impact of over 20,000 natural, technological, and complex disasters from 1900 to the present day. They define three disaster types relating to climate change, including climatological, hydrological, and meteorological disasters. Climatological disasters include drought and wildfire, and hydrological disasters mean flooding and landslide. Meteorological disaster is defined by extreme temperature, fog, and storm. Therefore, a statistic from 2000 is shown below.

Table 1.1 Climate disaster statistic on the United Kingdom from 2000 to 2019 (EM-DAT, 2020)

Year	**Disaster subgroup**	**Occur-rence**	**Total deaths**	**Injured**	**Affected**	**Homeless**	**Total damage ('000 US$)**
2000	Hydrological	3			1440		5,918,150
2000	Meteorological	3	16	4	20100		1,500,000
2001	Hydrological	2			240		
2002	Hydrological	3	1		750		
2002	Meteorological	2	14				400,050
2003	Meteorological	1	301				
2004	Hydrological	1		8	1000		96,000
2005	Meteorological	4	11		3000		700,000
2007	Hydrological	3	14		340200	30000	8,448,000
2007	Meteorological	1	13				1,200,000
2008	Hydrological	2	8		3300		50,000
2008	Meteorological	1					
2009	Hydrological	1	3		3900		484,000
2009	Meteorological	2	5	47	180		
2010	Meteorological	2					500
2012	Hydrological	5	8		3785		2,946,000
2013	Hydrological	1	2		600		1,500,000
2013	Meteorological	4	771		4200		
2014	Hydrological	1			540		624,000
2014	Meteorological	1	5		18000		100,000
2015	Hydrological	1			48000		1,200,000
2015	Meteorological	1	3		15600		1,200,000
2017	Hydrological	1			70		
2018	Meteorological	2		4			
2019	Hydrological	1	1				
2019	Meteorological	1	5				

By Table 1.1, the total death, total affected, and the total damage in the previous two decades are shown. The total death is 1181, and the total affected is 494968. Moreover, the total damage is US$ 26,366,700,000. The highest occurrence took place in 2013, and it is five in a year. Two extraordinary death tolls occur in 2003 and 2013 because of the substantial heatwave (Burt, 2004, Elliot et al., 2014). For total affected and total damage, they are the largest in 2007 as there were a large-scale of flooding in the summer (Blackburn et al., 2008). Also, the flooding created three thousand homeless persons.

Apart from the fatal records counted by EM-DAT, there are always disruptions on seaports and airports because of adverse weather (BBC, 2020, Carpani et al., 2019). The heatwave in 2019, for example, caused hundreds of cancellations and lengthy delays in seaports and airports. Except for the direct impact, there are some secondary impacts due to the disruptions on approach roads and railways. The delays come with considerable economic losses (Peterson, 2013). Therefore, it is urgent to assess climate threats in multiple dimensions for seaports and airports.

Department for Environment, Food and Rural Affairs (DEFRA) issued the Climate Change Act 2008, which identifies a framework for the UK to reduce its greenhouse gas emissions and adapt to climate change. In summary, the Act defines measures to set emissions reduction targets, produce annual reports, the creation of an independent advisory body, the ability to introduce an emissions trading scheme, and a procedure for looking at adaptation. It is under Section 62 of the Act that the power to direct statutory undertakers to report on climate change adaptation is created. Nine seaport authorities and nine airports, which were recognized as critical infrastructures, have been invited to write a climate change adaptation report. After reviewing the seaport and airport functions, the key climate change risks are listed and assessed by different authorities independently. The risk issues mentioned are reliable references for the construction of climate risk and resilience indexes.

One hundred thirty-six of the world's largest coastal cities have been assessed for the present and future flood losses by the Organisation for Economic Co-operation and Development (OECD). Average global flood losses in 2005 are calculated to be approximately US$6 billion per year, rising to US$52 billion by 2050 with the projection on socio-economic change only. Because of the increasing climate threats, present adaptation measures will need to be enhanced to avoid unacceptable losses of more than US$1 trillion per year (Hallegatte et al., 2013). Total dollar cost and the annual loss as a percentage of a city's wealth is two paths to measure the climate. Another is to look at annual losses as a percentage of a city's wealth, a proxy for local vulnerability. Using total dollar cost as the parameter, Guangzhou, China; Guayaquil, Ecuador; Ho Chi Minh City, Viet Nam; Abidjan, Ivory Coast are the most vulnerable among the all assessed coastal cities. The report also notes that flood risk may be raised in locations that are not vulnerable today, letting governments and citizens unprepared. The five cities with the most significant estimated increase in 2050 are Alexandria, Egypt; Barranquilla, Colombia; Naples, Italy; Sapporo, Japan; and Santo Domingo, Dominican Republic. They are totally different from the original top five cities.

1.3. Primary Research Questions and Objectives

Seaports and airports are strategically important to the UK mentioned in the Climate Change Act 2008. By studying the background information for climate change impacts and adaptations, this thesis was driven by three research questions, based on the literature review of existing knowledge:

- How can we assess the climate change impact and the associated risks facing seaports and airports?
- What are the similarities and differences of climate change adaptations to seaports and airports for cross referencing?
- How can we assess the global climate resilience by integrating all local climate impact together?

Starting with an overview of the above research questions, the overall aim is to measure the climate risk in both national and global dimensions. Thesis aims achieves the following three objectives:

- To identify climate risk and resilience indices to seaport and airport planning;
- To evaluate the risk of climate change and adaptation necessity in the UK seaports and airports;
- To combine the knowledges on climate risk assessment, centrality analysis, and shipping routing modelling to evaluate the global climate resilience.

1.4. Scope of Research

The research scope is set up to serve the core of this thesis, which argues the importance of enhancing the awareness of the authorities' consideration of the impacts of climate change and its effects on seaports and airports, and will suggest adaptation strategies to cope with climate change risks mainly from the perspectives of risk assessment and planning. Seaports and airports are both key nodes for transferring goods and people. Therefore, they have a huge potential to build up connections for enhancing the resilience of transportation system in the national level and in global level by three objectives mentioned in Section 1.2. On the other hand, the future climate risks in different places may not increase in the same way as the estimation from OECD in Section 1. Therefore, the first two objectives, identifying climate risk and resilience indexes to seaport and airport planning and evaluating the risk of climate change and adaptation necessity in the UK seaports and airports, achieves the research questions in national level. Furthermore, nine seaport authorities and nine airport authorities have been invited by the UK government to prepare the climate change adaptation reports. They have given the foundation by responding possible regional climate risks on seaports and airports. Also, they are strategic infrastructures chosen by the government such as Heathrow airport, Manchester airport, Felixstowe port and Forth ports. Therefore, they can be chosen as regional representatives for climate risk and resilience assessment in coming chapters.

On the global side, 136 coastal cities are chosen for observing the changes of shipping routing. By OECD study, climate change is threatening the world in a social and economical way drastically. However, OECD has just assessed the consequence on flooding.

Although this thesis looks at the global impacts of climate change and adaptations, considering that the complexity and diversity phenomena of climate change across different geographies, most of the literature and data are UK-based with the support of academic and industrial domain experts. However, it would not be taken as a limitation but a practical approach to fill the gaps among regional studies focused on the UK and the under-researched areas, including the utilisation of an FER modelling method for CCRI assessment and the comparative study of climate risks and adaptation on seaports and airports.

The novelty of this study includes:

- A nationwide survey investigating the impacts of climate change on the seaports and airports in the UK;
- A comparative study involving climate adaptation reports from nine seaports and nine airports, which offers workable recommendations and global references for adapting to climate change on other transportation systems and regions;
- Developing a climate change risk indicator (CCRI) framework and a climate resilience indicator (CRI) framework to assess the climate resilience for port cities and airport cities;
- A centrality analysis investigating the network vulnerability of the global shipping network, including 136 coastal cities;

- A shipping routing model investigating the changes on routing, depending upon the climate changes.

By listing out the objectives and the possible work packages, chapters are arranged to build a thesis structure.

1.5. Structure of the thesis

The thesis contains eight chapters. Following the introduction of research background, primary research questions, objectives, and scope in Chapter 1. It is based on the information from some international organisations including EM-DAT and OECD. Then, the research questions and objectives are set up accordingly, and the thesis present the in a structure that can response to the objectives accordingly.

Chapter 2 presents literature review on climate change adaption in seaports and airports, such as Climate impact assessment and cost-benefit analysis. A systematic review resulting in 128 papers from 92 internationally recognised academic journals, in November 2019. The review of publications over the past decade allows us to identify the emerging issues and relevant themes, how these issues and themes have evolved over time, and what are the challenges to be addressed in the future. The scholars are more altered on seaports more than airports. Then, it is resulted that cross-disciplinary tools are needed for assessing the climate risk and resilience for a seaport and for a network. Different multiple-criteria decision analysing methods have been compared and introduce for implementing assessment framework for local analysis. Then, graph theory and centrality assessment are introduced to connect a set of local indicators to a network analysis.

Chapter 3 present a the CCRI framework on seaports and airports. It explains the methodology of the FER model and the implication on the CCRI framework by the climate data from different organisations. First, climate vulnerability assessments and climate change adaptation reports on seaports have been reviewed. Then, open data from the Meteorological Office (Met Office, 2018), Climate Projection (UK Climate Projection, 2018), and British Oceanographic Data Centre (BODC) (British Oceanographic Data Centre, 2018) have been collected as a fuzzy input for the CCRI framework. Then, Fuzzy Evidence Reasoning (FER) within the context of the CCRI framework has been presented to prove the fitness of CCRI network. Then, FER approach on the CCRI assessment has been presented step by step. Then, the fuzzy input monthly datasets of twelve strategic seaports have been chosen for analysis. Then, the result with different locations and months have been presented, and the future data has also been assessed by inputting the forecasting data by CCRI framework. Then, the eleven strategic airports are assessed by the same CCRI framework as a cross reference for enhancing the climate resilience of seaports and airports together regionally to reflect the dynamic evolving climate risks. The result of a nationwide survey on the climate adaptation reports for seaports, and the construction of the CCRI framework is elaborated steps by steps, and twelve seaports have been chosen for evaluation, by the locations and months. Also, a comparison between now and 2050 is done for observing the climate risk changes in the future.

Chapter 4 presents the CRI framework on seaports and airports. explains the methodology of the FER model with Analytic Hierarchy Process (AHP) method for the implication on the CRI framework by the chosen climate data and the regional social-economic data for the regions of the chosen twelve seaports. Therefore, local climate vulnerability assessments, which cover a larger area than that of a seaport, are reviewed. Then, climate exposure, vulnerability, and adaptive capacity are defined for structuring the CRI framework. Then, open regional and logistic data from thirteen organisations, excluding the organisations mentioned for Chapter 3 and 4, is added for the analysis. Also, AHP is reviewed to prove its suitability for FER model. Then, the result of a nationwide survey based on the CRI network is done for weighting the criteria. Then, the evaluation for airports by CRI framework is presented. The same set of open data is collected for eleven strategic airports, and the result has been presented for comparison. Also, the comparison between the questionnaire results of seaport and airport are used for comparison.

Chapter 5 explains the centrality assessment for 136 largest coastal cities as a reference from the Organisation for Economic Co-operation and Development (OECD) for the vessel routing assessment in Chapter 6. First, vulnerability and resilience are defined by literature reviews. Then, centrality assessments in maritime transportation have been reviewed. Assessment framework has been referenced from Liu et al. (2018) and Wan et al. (2017) for performing multi-centrality assessments. The top 20 seaports in centrality assessment have been chosen for observing the changes independently in Chapter 6. Finally, comparative analysis for global vulnerability and seaport vulnerability has been assessed to understand the different vulnerabilities for different ports.

Chapter 6 presents the global shipping network assessment, with the 136 largest coastal cities. First, articles related to seaport disruption due to climate extremes is reviewed. Then, the needs of multiple-objective decision support for environmental sustainability in the maritime industry have been explained with the reference from Mansouri et al. (Mansouri et al., 2015). Also, the suitability of Artificial Bee Colony (ABC) algorithm has been stated for shipping routing problems. Then, the problem formulation is explained. After that, solution methodology and numerical experiments are shown.

Finally, Chapter 7 concludes with the key findings from this study. The outcomes of the study are stressed by demonstrating their academic and practical contributions to realise the more effective design and implementation of adaptation plans. It also contains the research limitations and recommendations for future research directions.

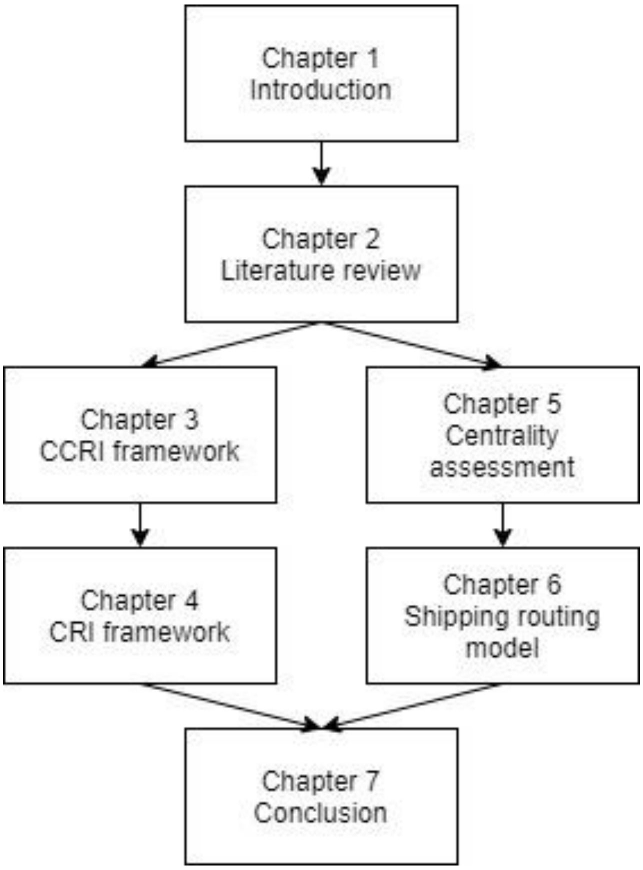

Figure 1.1 Thesis structure

Chapter 2 Literature review

2.1. Summary

This chapter presents a systematic review of climate change research on transportation systems, specifically, to understand the current evidence base on climate vulnerabilities, adaptation strategies, and operation management, in the context of road and rail transportation systems. The aim is to investigate the existing developments in research publications over the past decades. It starts with a general introduction about climate changes and their impacts, as well as adaptations for climate change. Then, selected publications are systematically evaluated, in terms of the geographic location of research, leading authors and co-authorships, domain methodologies, key research themes, and research scales. Most importantly, the selected papers are critically analysed by categorising them into several dimensions as a research result of the systematic reviewing process, to understand the status quo and potential challenges we face systematically. These themes cover the impacts of climate change on road/rail transportation, climate risk assessment, transport asset management, climate planning and policy, and adaptation of transport infrastructure to climate change. This review contributes to providing researchers with valuable references for future research, and it offers industrial practitioners and planners constructive insight and practical guidance, on climate adaptation, risk analysis, transport planning and other vital topics. Then, the research methods and research interests should be further clarified with relevant literature

2.2. Systematic review of climate change research on seaports and airports

In previous years, there were some literature reviews in similar research areas. However, they did not focus on seaports, airports, sea-level rise (SLR) and flooding. For examples, Jonkeren and Rietveld did another review for waterborne transport infrastructures with an economic focus (Jonkeren and Rietveld, 2016), and Lee did a review with a focus on emission reduction for all transport modes (Lee, 2007). Therefore, it is necessary to prepare this review for studying the climate adaptation for seaports and airports independently, and then a comparative analysis can take place upon the review finding (Poo et al., 2018b).

2.2.1. Methodology of literature review

To carry out a comprehensive literature review of seaport and airport adaptation to climate change, we have set up a systematic analysis for article searching and selection. Regarding

Wan (Wan et al., 2017) and Luo (Luo and Shin, 2016), we can divide the whole data collection process into three steps:

1. Online database searching;
2. Article screening;
3. Final refining and analysing.

Firstly, we collected papers on climate change adaptation of seaports and airports with a focus on flooding and storms from all the peer-reviewed academic journals on Web of Science (All Database). It is one of the most comprehensive multidisciplinary searching platforms for academic research (Hosseini et al., 2016). We used two strings, "(flooding or flood or adapt or adaptation or resilience or fog or heatwave) (airport or seaport or port)" and "(flooding or flood or fog or heatwave) (resilience or adapt or adaptation) (airport or seaport or port)", as "Topic" items to perform the searching process. Throughout the searching process, many strings are searched, and the two strings mentioned can summarise all the results. The search was completed in November 2019, covering the period from 1970 to 2019. 567 relevant papers were collected.

Secondly, we conducted a two-stage screening process to secure the relevance and quality of the selected articles. In the first stage, we sorted out the peer-reviewed journals and eliminated the book chapters, conference proceedings, editorial materials, and non-peer-reviewed journals. The peer-reviewed journal papers were chosen for analysis because it is the most guaranteed type of documents for the acceptance of the scientific community (Bergström et al., 2015). We reduced the number of articles from 567 to 404. In the second stage, we studied titles, keywords, and abstracts of the chosen 404 articles to confirm their relevance. For example, some articles related to an ecosystem (Hirst et al., 2016) and other climate change impacts (Tham et al., 2011), which are irrelevant to climate extremes, were eliminated. After the second screening, the number of the selected articles was reduced to 153. The articles are eliminated if they are not climate change analysis, climate impact assessment, climate vulnerability/ risk assessment, cost-benefit analysis, adaptation strategies, stakeholder response analysis, construction, or operation studies.

Finally, we carefully conducted the full-text review for the refined 153 articles. As a result, the articles that have no focus on climate extreme impact on transportation, are also eliminated. After the final refining process, 128 articles remained. We analysed the articles by the distribution of their publishing years, authors, journals, regions, transportation modes, research methods and scales. We found the research interests and the corresponding trends of different research themes. Furthermore, we analysed the connection of leading authors through their collaborative papers. Finally, we compared the studies on seaports and airports to guide the directions of further studies.

2.2.2. Analysis of studies

The analysis is based on statistical results and presented by different figures and tables in the following parts. From the statistical results, an overview can be done statistically, including the trend of study. Distribution by different regions, transport modes, research methods are considered. Also, research interests are defined.

2.2.3. Trend of study

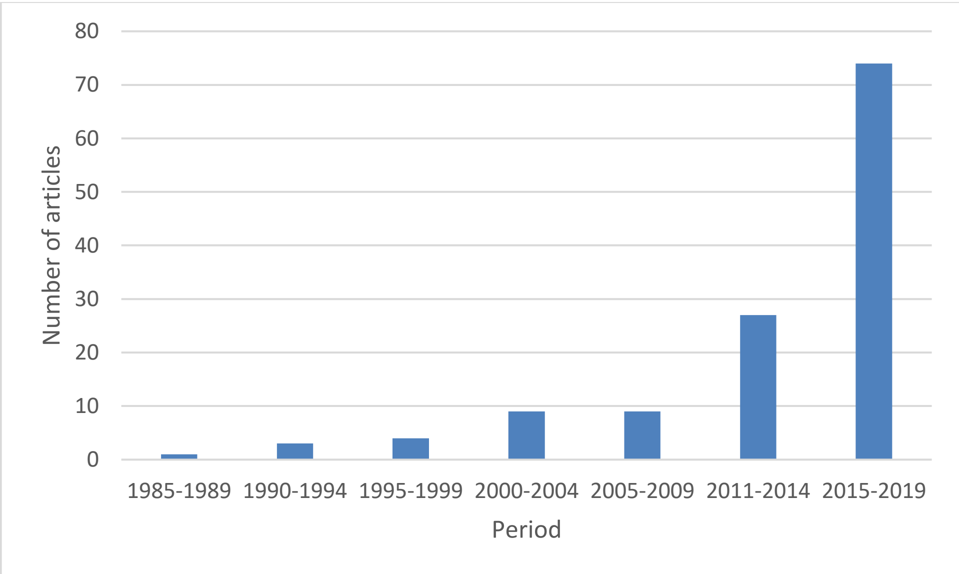

Figure 2.1 Study distribution by publishing year

The refined 128 journal articles are distributed from 1985 to 2019 and represented in Figure 2.1. The earliest refined journal is from 1985. 2015, 2016, 2017 and 2018 are the years with the highest number of journal articles: 17, 17, 18 and 17 respectively. The number of corresponding papers is increasing rapidly. In the period of 2011 - 2014, the number of articles is three times more than that of 2005-2009, while in the period of 2015-2019, the number of articles trebles compared to that of 2011-2014 and is more than the total before 2014, even though (at the time of writing) 2019 is not over. Such a growth clearly indicates the importance and urgency of the research topic and well reflects the fact that climate change involving both mitigation and adaptation is of high priority on both the national and international research agenda. It is foreseen that there are increasing studies and relevant outcomes and publications in this field given the increasing effect of climate change on transportation and our social welfare.

2.2.4. Distribution by journals

After assessing the trend of studies, it is necessary to assess the articles by different aspects. The top journals, which means more than 3 articles, are listed in Table 2.1. Among all articles, Climatic Change is the most referenced journal as it published 7 journal articles that were related to the topic. Other leading journals include Natural Hazards, Journal of Coastal Research, Maritime Policy & Management, Journal of Environmental Planning and Management, Ocean & Coastal Management, Regional Environmental Change, Sustainability Science, and Transportation Research Part B. If the journals have the same number of articles, we list them in alphabetic order in the journal list. It is clearly seen that the topic has diversified features and attracts attention and interest from a wider audience from coastal research, geographical science, ocean engineering and environmental and sustainability studies.

Table 2.1 Top 9 journals

Rank	Journal Title	No. of articles
1	Climatic Change	7
2	Natural Hazards	5
3	Journal of Coastal Research	4
4	Maritime Policy & Management	4
5	Journal of Environmental Planning and Management	3
6	Ocean & Coastal Management	3
7	Regional Environmental Change	3
8	Sustainability Science	3
9	Transportation Research Part B	3

2.2.5. Distribution by authors

This section evaluates the distribution of the leading authors. Table 2.2 shows the top authors. Among all articles, Austin Becker and Robert Nicholls are the highest contributing scholars in the field. There are also 15 more authors contributing more than 2 articles. Analysing the distribution by authors could also help us to identify the strong research groups/labs in the world in the investigated area. Statistical analysis on the papers of multiple authors from different research groups indicates that so far there is no significant critical mass being formed from the listed leading authors, which reveals that the studies in the field are being carried out rather individually and the issues are being tackled from different perspectives based on the expertise possessed by different groups. Therefore, it shows a good potential to integrate the complementary expertise from the leading authors to match the diversified features of climate adaptation research, involving hazard analysis, impact assessment, risk modelling, resilience engineering, geographical studies and environmental and sustainability science.

Table 2.2 Top 11 authors

Rank	Journal Title	No. of articles
1	Becker, Austin	7
2	Ng, Adolf K.Y.	5
3	Esteban, Miguel	4
4	Sierra, Joan Pau	4
5	Corfee-Morlot, Jan	3
6	Fischer, Martin	3
7	Hallegatte, Stéphane	3
8	Lam, Jasmine Siu Lee	3
9	McEvoy, Darryn	3
10	Nicholls, Robert	3
11	Zhang, Anming	3

2.2.6. Distribution by regions

Apart from assessing the authorship of the journal articles, we investigate the regions of studies through the analysis of locations of case studies and the authors' affiliations. The regions of the case study presented are the leading factor, and the first authors' institutions are the second factor if there is no case study in a journal article. Then, the result is shown in Figure 2.2. Europe occupies 31%, involving 39 articles. It is followed by North America, Africa, Asia, Oceania, Latin America and the Caribbean. In general, European and American academic institutions (accounting for 54% of the total) retain a world leading position in climate change adaptation with a focus on extreme weather events. It provides the useful insights as to where the possible best practices and solutions to EWEs in seaports and airports are in the world nowadays.

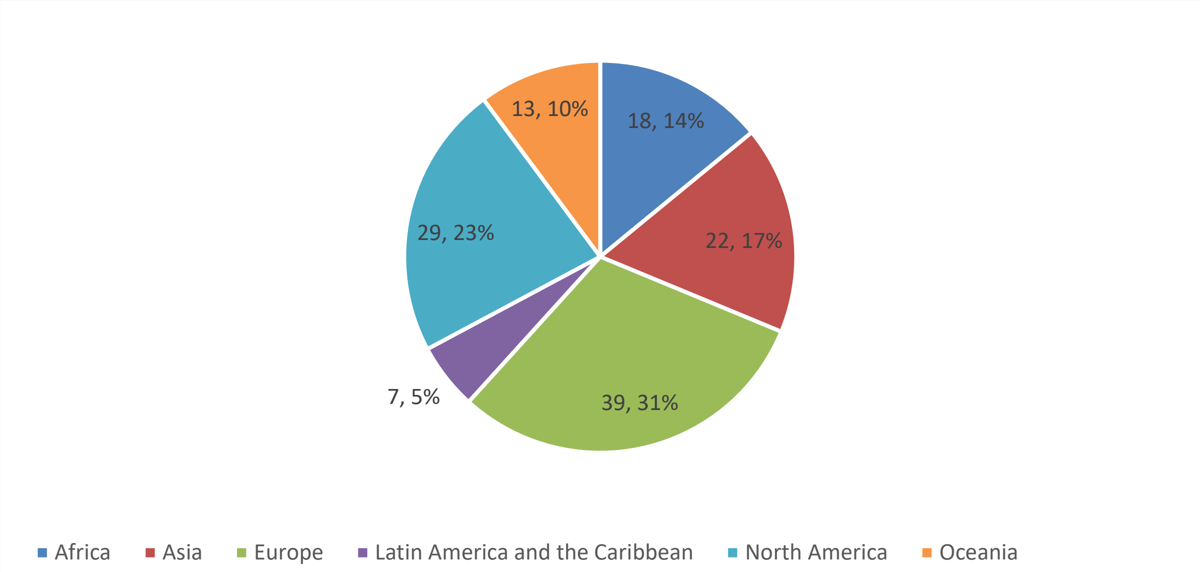

Figure 2.2 Distribution by regions

2.2.7. Distribution by transportation modes

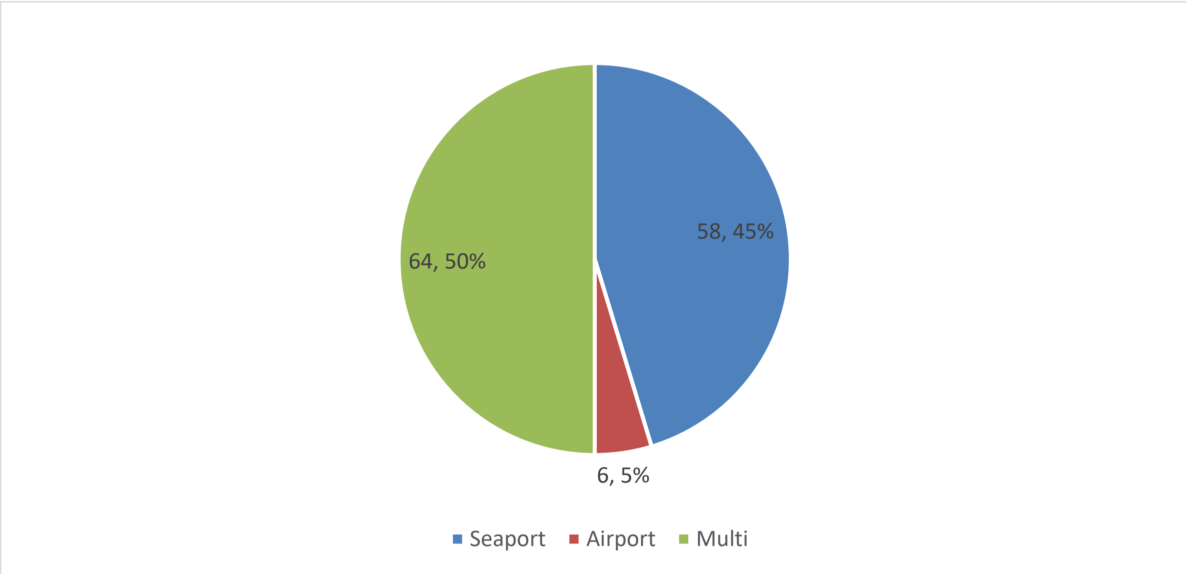

Figure 2.3 Distribution by transportation modes

In this section, we analyse the difference between the relevant studies in seaports and airports. By reviewing all the 128 papers, we carry out the analysis by separating them into three groups, “Seaport”, “Airport” and “Multi”. It is because some regional coastal assessments have not stated that they are unique for any transportation mode (e.g. airports or seaports), instead they tackle large regions involving both seaports and airports. The result is shown in Figure 2.3.

“Multi” has the largest ratio of 50%, involving 64 articles. “Seaport” and “Airport” have 39% and 4% respectively. It reveals two important pieces of information that can trigger some interesting future studies. One is that within the context of adaptation to seaports and airports, there are high synergies between airports and seaports given that 50% of the investigated papers treat them together. The other is that seaports attract more research attention in the area.

2.2.8. Distribution by research scales

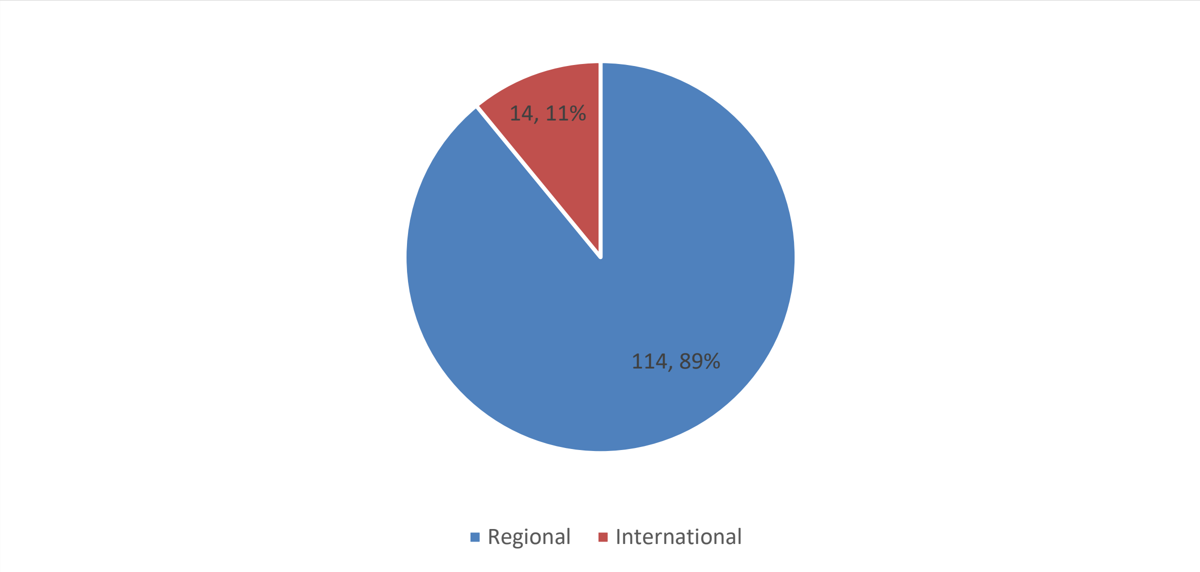

Figure 2.4 Distribution by research scales

The research scales can be defined as “Regional” and “International”. If the academic journal includes comparison between nations or case studies from more than one nation, it is defined as “International”. Otherwise, it is defined as “Regional”. The result is shown in Figure 2.4. Quantitative research takes an important role in these kinds of studies as it got 114 articles and 89% in total.

2.2.9. Distribution by research types

The simple division between quantitative research and qualitative research is simply conducted by their basic characteristics. Quantitative research considers hard science which consists of statistical analyses (Mugenda and Mugenda, 1999). On the other hand, qualitative research considers soft science in which words are more important throughout the whole research. The result is shown in Figure 2.5. Quantitative research takes an important role in these kinds of studies as it got 89 articles and 70% in total. The remaining is qualitative research, which consisted of 39 articles and 30% in total. The main quantitative methods used include simulation and mathematical modelling. A simulation method is used to study the operation of a real-world or a theoretical process/system under various pre-set circumstances for different purposes (e.g. numerical testing, observing behaviour, optimising performance, or exploration of new states). Mathematical modelling refers to those applying mathematical concepts and languages to describe and represent objective reality. The qualitative methods are conceptual work and case studies. The conceptual work includes analysis on concept issues such as definitions, properties, theoretical framework and conceptual modelling. A case study refers to an in-depth examination of a person, community or situation, which usually can be achieved via interviews. By reviewing the 128 papers, it is also found that a lack of data is a common problem discussed in both qualitative and quantitative studies. Therefore, how to address the unavailability and uncertainty in data to support the rational decision in this area remains unclear, wanting solutions from future studies to be found.

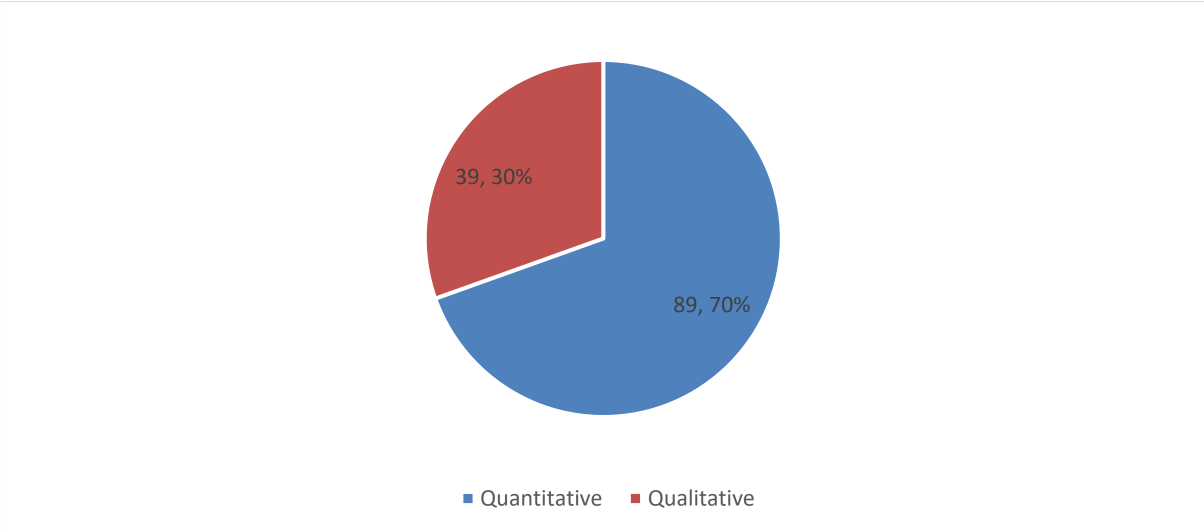

Figure 2.5 Distribution by research types

2.2.10. Distribution by research methods

Following the analysis in Section 2.2.9, this section analyses the detailed research methods in the 128 papers, including:

- Review
- Survey
- Framework
- Modelling
- Simulation

The studies that involve more than one method are counted multiple times. The result is shown in Figure 2.6. The most common method is “Modelling” representing 54 articles in total. The second and third most common methods are “Framework” and “Review”, where the numbers of articles are 42 and 40, respectively. “Simulation” and “Survey” are at the bottom, relating to 11 and 9 papers, respectively.

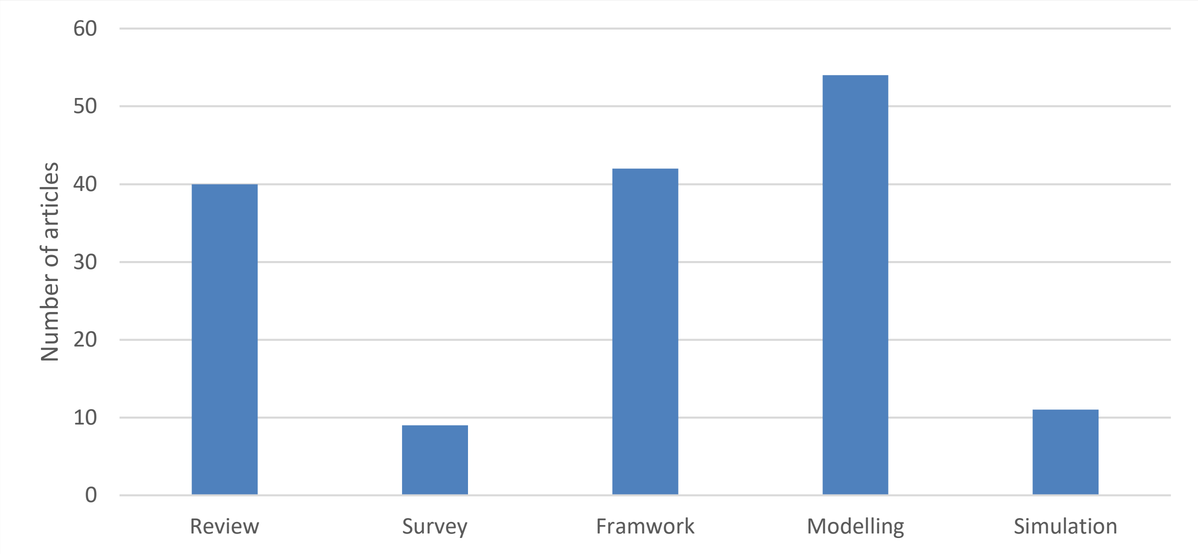

Figure 2.6 Distribution by research interests

2.2.11. Distribution by research interests

In terms of research topics, seven types of research interests are defined:

- Climate impact assessment
- Vulnerability/ Risk assessment
- Adaptive strategies
- Cost-benefit analysis
- Stakeholder analysis
- Construction
- Operation

The definitions of Climate impact assessment (CIA), vulnerability assessment and adaptive strategies are in line with those from an IPCC report (IPCC, 2014a). The report presents a fundamental adaptation planning framework containing such important concepts. CIA is a study describing the trend of climate change, where the impacts can be rising temperatures, SLR and others. A vulnerability assessment for climate change is the process of identifying and quantifying the vulnerabilities in a specific region or infrastructure. Adaptation strategies mean the case study of local and regional transportation infrastructure by introducing the adaptive management of a region or transportation system. Besides, risk assessment requires the combination of study in threat, vulnerability and impact factors (Liu et al., 2012). Cost-benefit analysis based on the economic analysis of system or infrastructure adaptation strategies means the case study of local and regional transportation infrastructure by introducing the adaptive management of a region or transportation system. Stakeholder analysis is a methodology to facilitate institutional and policy reform processes by accounting and often incorporating the needs of those who have an interest in the reforming under consideration (Schmeer, 1999). Construction and operation mean the studies, not in the adaptation planning process but the post-planning process. Some investigated papers contain more than one topic and hence are counted multiple times in the statistics in Figure 2.7.

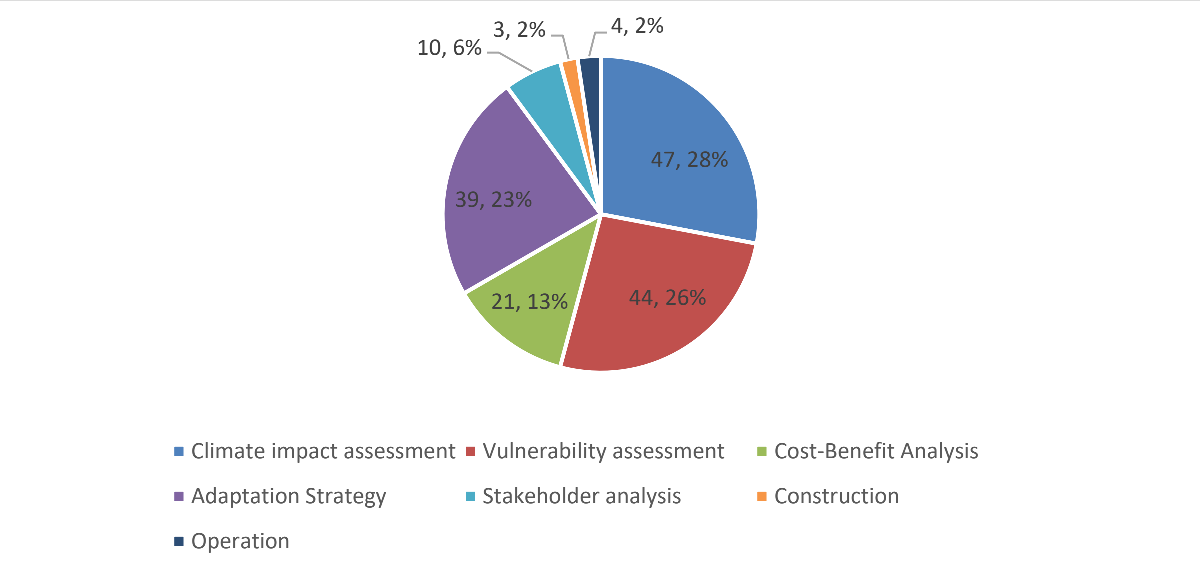

Figure 2.7 Distribution by research interests

The most common research method is CIA and there are 47 articles occupying 28%. It is followed by vulnerability/risk assessment, adaptation strategies, cost-benefit analysis stakeholder analysis, operation, construction. Obviously, studies in the adaptation planning process are far more than those in the post-planning stage and dominate the research on seaports and airports adaptation to flooding and storms. It indicates that the current construction and operations of airports and seaports have not yet considered climate adaptation significantly. Adaptation strategies are made largely based on CIA, receiving more and more support from vulnerability assessment, risk assessment and cost-benefit analysis, to make the climate adaptation research in seaports and airports more systematic. Furthermore, stakeholder analysis shows a huge potential to grow in the next decade when more adaptation strategies are developed, requiring the balancing of different interests of multiple stakeholders for their implementation.

2.2.12. Evolution of the studies

Due to the complexity of studies, the evolution of the studies is discussed from 7 perspectives with respect to the 7 topics. The directions of the research are researched in chronological order of the 8 topics one by one after the comparison of the publication year of the first paper of each topic in Table 2.3.

Table 2.3 The earliest years for different research interests

CIA	Vulnerability/ Risk assessment	Cost-benefit analysis	Adaptation strategies	Stakeholder analysis	Construction	Operation
1985	1997	2013	2008	2013	2016	2015

In 1985, Prasad and Reddy started to assess the sea-level fluctuation monthly and annually in India and recorded this in academic journals for the first time (Prasad and Reddy, 1985). In 1991, apart from sea level rise, Gornitz designed the coastal vulnerability index (CVI) to raise high-risk coastal segments with a case study in the U.S. (Gornitz, 1991). A few years later, Dhaw and Forbes expanded the range of CIA from SLR to flooding and storms (Dhaw and Forbes, 1995). In 1999, Hubbert and McInnes designed a storm surge inundation model for coastal planning in Australia (Hubbert and McInnes, 1999). In 2000, Pirazzoli makes a flooding statistical probability study on the Atlantic coast of France (Pirazzoli, 2000). In 2003, Hunter makes a tailor-made SLR assessment for seaports in Tasmania (Hunter et al., 2003). In 2009, CIA is integrated with Geographic information system (GIS) for assessing digital elevation model (DEM) to make an Integrated Coastal Zone Management Plan by Snoussi (Snoussi et al., 2009). In other words, scholars start to combine CIA with vulnerability assessment by GIS spatial analysis. In 2010, Frihy et al. contribute to the evolution by upgrading the SLR assessment from recording to forecasting its values in different scenarios (Frihy et al., 2010). In 2015, Becker et al. combine CIA with vulnerability assessment and adaptation strategies from a whole climate adaptation planning perspective (Becker et al., 2015). In 2017, there are two special assessments for seaports. One is for harbour operability (Sierra et al., 2017b), and one is for studying extreme wind events (Repetto et al., 2017).

In the late 90s, the El-Raey team undertook two vulnerability assessments of the coastal zone of Egypt, Nile Delta and Port Said Governorate (El-Raey, 1997, El-Raey et al., 1999). They used remote sensing for GIS spatial analysis. After a decade, studies on vulnerability assessment arrived at a new stage. In 2008, Sterr integrates vulnerability assessment with adaptation strategies by clustering the assessment into a smaller region (Sterr, 2008), and In 2008, Reid establishes a framework of climate risk analysis of seaports (Reid, 2008). At the same time, GIS spatial analysis by DEM began to be widely used in vulnerability assessment (Gravelle and Mimura, 2008, Snoussi et al., 2009). In 2010, Briguglio connects risk assessment with adaptation suggestions (Briguglio, 2010). In 2012, Keokhumcheng et al. assess the flood risk in airports (Keokhumcheng et al., 2012). Bangkok Suvarnahumi Airport is used for the case study. In 2015, Akukwe and Ogbodo connect the studies of vulnerability assessment to emergency planning for setting up vulnerability indices and ranking these indices across the 13 costal zones they investigated (Akukwe and Ogbodo, 2015). At the same time, Musekiwa et al. set up a risk analysis table from vulnerability assessment to connect risks and vulnerabilities (Musekiwa et al., 2015), and Zhang and Lam estimate the economic losses of port disruption due to extreme wind events (Zhang and Lam, 2015). In 2016, Zanetti et al. propose a Climate Change Vulnerability Index (CCVI) with a case study in Brazil (Zanetti et al., 2016). In 2017, Lam et al. develop a risk assessment framework for cargo ports and cyclone risk mapping for critical coastal infrastructure for East Asian seaports (Lam et al., 2017, Lam and Lassa, 2017), At the same year, Mutombo and Olcer provide a global climate risk indicator to guide further adaptive initiatives in seaports, and Toimil et al. provide insights into the possible consequences of inaction for a range of future scenarios based on changes in climate and socio-economics over the most relevant sectors (Toimil et al., 2017). Zevenbergen et al., Aerts et al., Komugabe-Dixson et al. and Monioudi et al. provide case studies in Alexandria city, Los Angeles, Port Vila, Jamaica and Saint Lucia respectively (Aerts et al., 2018, Komugabe-Dixson et al., 2019, Monioudi et al., 2018, Zevenbergen et al., 2017). In 2018, Tsalis et al. design a methodology to evaluate the disclosure practices of organisations related to climate change risks for international airports, and Forzieri et al. escalate impacts of climate extremes on critical infrastructures in Europe (Forzieri et al., 2018). Furthermore, Yang et al. develop a new risk analysis model for climate risk quantification in a situation where objective data relating to risk parameters are not available (Yang et al., 2018). In 2019, Yang et al. develop a composite climate change vulnerability index for small craft harbours.

In 2013, Nicholls et al. summarise the coastal planning experience from England and Wales. They started to include cost estimation. After that, there is a vulnerability assessment, including cost estimation (Musekiwa et al., 2015) . Genovese and Green began to predict the damage of storm surge by modelling methods in 2015 (Genovese and Green, 2015) and Hoshino et al. commence to estimate and compare the loss caused by future storm surges with and without adaptation strategies in the Greater Tokyo area (Hoshino et al., 2016), and cost-benefit analysis is formally integrated into the rational development of adaptation measures. In 2017, Becker et al. estimate cost and materials required to retrofit US seaports in response to SLR (Becker et al., 2017). At the same year, DiSegni et al. assess the costs for adaptation of marine constructions to SLR (DiSegni et al., 2017). In 2018, DiSegni et al. model the adaptation investment to climate change-related disaster, by two landlord seaports, and Sriver et al. characterise uncertain SLR projections to support investment decisions (Sriver et al., 2018). In 2019, Kontogianni et al. develop a composite climate change vulnerability index for small craft harbours (Kontogianni et al., 2019), and Sierra estimates the economic impact of overtopping and adaptation measures in Catalan Ports due to SLR (Sierra, 2019). At the same time, Randrianarisoa and Zhang analyse the size and timing of investment in climate adaptation for ports, and in 2019, Esteban et al. summarise experiences based on land subsidence in Indonesia and Japan (Esteban et al., 2019).

The earliest article presenting the climate change adaptation element in seaports and airports is published in 2008 (Sterr, 2008). Afterwards, many articles with adaptation measures and strategies are published (Becker and Caldwell, 2015, Briguglio, 2010, Hoshino et al., 2016). Between 2012 and 2013, there are several review papers published to address the use of adaptive measures. Osthorst and Mänz provide a preliminary typology of forms of sectoral adaptation to climate change by literature reviews (Osthorst and Manz, 2012). At the same time, Wilby and Keenan identify evidence of different types of adjustment by following the flooding in Victoria, Australia (Wilby and Keenan, 2012). One year later, Becker et al. address a note for seaports on climate change adaptation. Furthermore, they discuss the needs and contributions of stakeholders of seaports (Becker et al., 2013). Afterwards, Acciaro et al. investigate successful innovations improving the environmental sustainability of seaports (Acciaro et al., 2014). In 2016, Mutombo and Olcer develop a three-tier (Policy-Management-Technology) framework for seaport Infrastructure adaptation. At the same year, Burbidge states a climate adaptation review on The European Organisation for the Safety of Air Navigation (EUROCONTROL) for European airports (Burbidge, 2016). In 2017, Becker uses boundary objects, different adaptation scenarios, to stimulate ideas of storm resilience for seaports (Becker, 2017). In 2018, Kim et al. integrate travel demand modelling and flood hazard risk analysis for evacuation and sheltering (Kim et al., 2018), and Li et al. establish an environmental adaptability measurement framework of human-sea economic system in Liaoning coastal area (Li et al., 2018). At the same year, Perumal implements a study based on community perspectives on climate change and climate-related migration in the Pacific island nation of Vanuatu. In 2019, Ng et al. provide insights on climate adaptation management from a major Canadian port (Ng et al., 2019), Trofimenko and Yakubovich justify the measures on adaptation of transport infrastructure facilities to climate change in permafrost zones (Trofimenko and Yakubovich, 2019).

After developing adaptation strategies for several years since 2008, Becker et al, and Peirson et al. state the importance of stakeholders' participation in the whole adaptation planning for seaports in 2013 (Becker et al., 2013) and especially for estuaries in 2015 (Peirson et al., 2015) respectively. Moreover, Burbidge records the consultation of European aviation stakeholders in climate change adaptation for airports in 2016 (Burbidge, 2016). In 2014, Nursey-Bray studied how the port governance on negotiating climate-adaptive management for facilitating regional, national and transnational networks and governance flows (Nursey-Bray, 2014). In 2018, Becker and Kretsch give a case study of Rhode Island about the leadership void on climate change. In 2019, McLean and Becker discuss decision-makers' barriers to climate and extreme weather adaptation.

In terms of the construction in the post-planning process, the previous articles focused on new construction methods as one of the adaptation measures. In 2016, Becker et al. developed a way to estimate climate-sensitive construction materials applied to seaport protection (Becker et al., 2016). At the same year, Chow et al. designed a new coastal structural concept for climate change adaptation in Hong Kong and undertook a relevant cost-benefit analysis (Chow et al., 2016). Sierra et al. suggest green measures for Mediterranean harbours under a changing climate (Sierra et al., 2017a).

As far as seaport and airport operations for climate adaptation, previous articles focused on extreme weather operations. In 2015, Herath et al. integrated spatial and temporal downscaling approaches to develop an intensity–duration–frequency (IDF) model for assessing sub-daily rainfall extremes for the Perth airport area (Herath et al., 2015). In 2016, Chhetri et al. used Container Terminal Operations Simulator (CTOS) to simulate extreme weather event impacts on a port operation (Chhetri et al., 2016). At the same year, Dunn and Wilkinson invented a network graph approach to increase the resilience of air traffic networks (Dunn and

M.Wilkinson, 2016). In 2018, Ryerson models the factors driving diversion airport choice (Ryerson, 2018).

2.2.13. Discussion on climate change adaptation one seaports and airports

There are three points to address before moving on to other chapters. First, there are various climate assessments on seaports and airports but a platform for further analysis and comparison. So, the comparative analysis between them is also needed to be conducted to cross reference the situation of both seaports and airports, and the possibilities of the emergency and humanitarian relief alliance between seaports and airports can be assessed. Second, it can be understood that climate change get more attention by governmental bodies and academics (Poo et al., 2018b).

Furthermore, there is a vast difference between them in terms of research topics. Airports have more research focused on the operation and climate vulnerability/risk assessment, while seaports are associated with other research topics as indicated in Figure 2.8. By integrating the finding of distribution by research interests in Figure 2.4, the significant research interest is assessing the climate impacts and vulnerability within a port city or a state. By a climate index platform for both seaports and airports, it can be a solution for connecting knowledge on both sides.

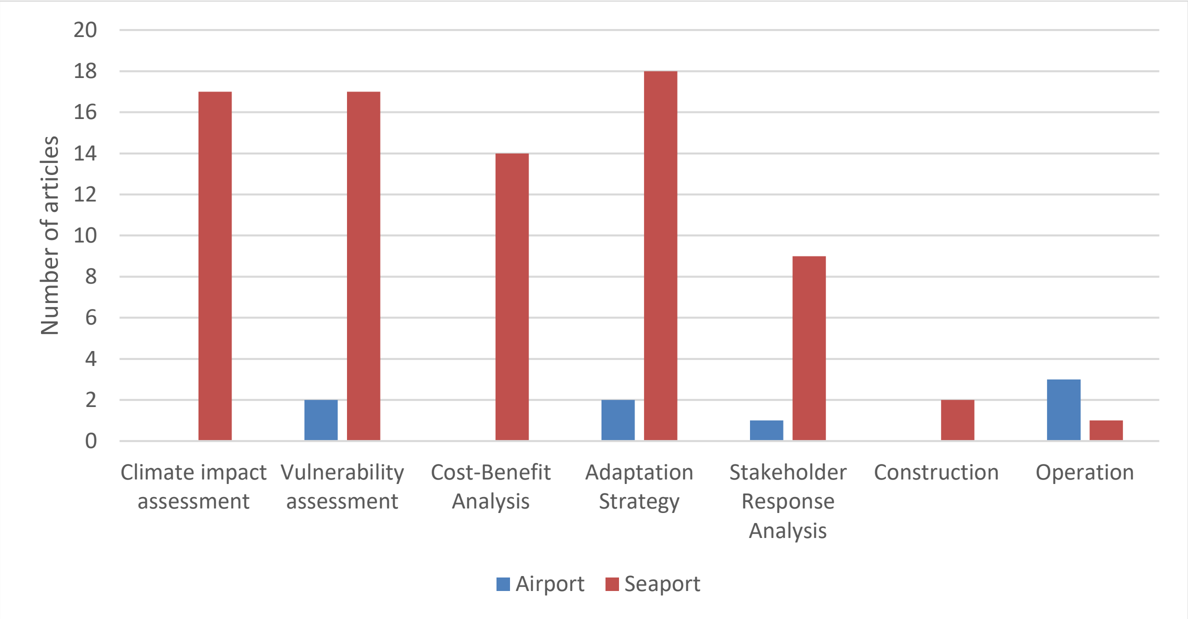

Figure 2.8 Distribution by research interests with a split of airports and seaports

The final issue needing to be addressed is that only 11% of journals provide global insight as shown in Figure 2.4, in which most of the climate impacts are international, and seaports are needed to function together for logistic. There are more studies required to be done on an international scale, for example an international assessment framework and a global shipping network assessment.

Therefore, internationally adaptable climate risks or resilience indexes, especially for seaports and airports, are needed to be constructed. It is can benefit the global logistic system. Also, a global shipping network is needed to be assessed on the climate resilience. One of the possible methods is to construct a shipping routing model by combining the knowledge on climate indexes and centrality assessment. There are more concerns comparing to existing shipping network (Liu et al., 2018, Wu et al., 2019), as they are needed compared by agglomerations. Therefore, the research questions are based on literature review and the objectives are set up in Section 1.2.

2.3. Review of multiple-criteria decision analysis

Climate adaptation on seaports and airports, which are critical transport infrastructures, is a complex issue, involving many variable systems and having many definitions as shown in Section 2.2. Therefore, decision making on climate adaptation requires complex interactions between exposure, sensitivity, and adaptive capacity, and it requires active participation by all relevant stakeholders and the early involvement in the process. Multi-criteria decision analysis (MCDA) of transport infrastructure projects have been assessed comprehensively by Broniewicz and Ogrodnik (2020). Therefore, the popularity of MCDA is assessed. By combining the other two studies on MCDA methods (Broniewicz and Ogrodnik, 2020, Lee and Yang, 2018), advantages and disadvantages of fourteen methods are analysed and listed below:

Table 2.4 Summary of multiple-criteria decision analysis

MCDA	Advantages	Disadvantages
Multi-Attribute Utility Theory (MAUT)	• Taking uncertainty into account; • Able to incorporate preferences.	• Requiring a lot of input; • Preferences need to be precise.
Analytic Hierarchy Process (AHP)	• Easy to use; • Scalable; • Not data intensive.	• Problems due to interdependence between criteria and alternatives; • Possibly inconsistencies between judgment and ranking criteria.
Analytic Network Process (ANP)	• Easy to use; • Capable of ranking parts of a multiple-criteria problem in a hierarchical structure.	• Difficult to provide correct network structure among criteria; • Unnatural finding takes places.
Case-Based	• Not data intensive;	• Sensitive to inconsistent data;

Reasoning (CBR)	• Requiring little maintenance; • Improving over time; • Adapting changes in environment.	• Requiring many cases.
Data Envelopment Analysis (DEA)	• Capable of handling multiple inputs and outputs; • Efficiency can be analysed and quantified.	• Does not deal with imprecise data; • Assumes that all input and output are exactly known.
Evidential reasoning (ER)	• Capable of handling different assessments • Suitable to analysis incomplete dataset	• It is compulsory to obtain decision-maker's true preferences,
Fuzzy Set Theory	• Allows for imprecise input; • Taking into account insufficient information.	• Difficult to develop; • Can require numerous simulations before use.
Simple Multi-Attribute Rating Technique (SMART)	• Simple; • Capable for combining any type of weight assignment technique; • Less effort by decision makers.	• Procedure may not be convenient considering the framework.
Goal Programming (GP)	• Capable of handling large-scale problems; • Producing infinite alternatives.	• It's ability to weight coefficients; • Typically requiring to be used in combination with other MCDM methods to weight coefficients.
ELECTRE	• Takes uncertainty and vagueness into account.	• Its process and outcome can be difficult to explain in layman's terms; • Outranking causes the strengths and weaknesses of the alternatives to not be directly identified.
PROMETHEE	• Easy to use; • Does not require assumption that criteria are proportionate.	• No clear method by which to assign weights.
Simple Additive Weighting (SAW)	• Ability to compensate among criteria; • Intuitive to decision makers; • Calculation does not require complex computer programs.	• Estimates revealed do not always reflect the real situation; • Result obtained may not be logical.
Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)	• Easy to use and program; • The number of steps remains the same regardless of the number of attributes.	• Its use of Euclidean Distance does not consider the correlation of attributes; • Difficult to weight and keep consistency of judgment.

VIekriterijumsko KOmpromisno Rangiranje (VIKOR)	• Providing a compromise solution with an advantage rate. • Solving problem in a fuzzy environment	• Hard to identifying criteria.

There are two highlights mentioned by Broniewicz and Ogrodnik (2020). First, AHP and TOPSIS are the most popular methods for making decisions for transport infrastructures. Second, the fuzzy set theory is an important element of modern multi-criteria analyses. In another words, fuzzy set theory can be merged with other methods, including AHP, TOPSIS, VIKOR, as modified versions to ease the implementation.

Among all fourteen methods, some of them have been chosen to apply in this study. As the dataset future climate data and adaptation details are incomplete, ER, Fuzzy Set Theory, and AHP.

ER is used as CCRI framework and CRI framework require the construction of a hierarchical structure accommodating the climate risk variables concerning different climate threats. Corresponding CCRIs and CRIs have been selected to assess each climate threat independently. In such a hierarchical structure, it is usually the case that the risk indicators at a higher level are also making use of the information produced at the lower levels. It is therefore essential to synthesise the risk performance against individual indicators from the lowest level to the top. In the process of assessing the climate risks, the two main uncertainties that decision-makers may encounter include multiple types of climate indices and incomplete future data set. ER requires the transformation from quantitative to qualitative assessments and is appropriate for utilising the two frameworks (Yang and Singh, 1994). The kernel of this approach is an ER algorithm developed from the concept of the Dempster–Shafer (D–S) theory, which requires modelling the hypothesis set with the requirements and limitations of the accumulation of evidence (Yang and Singh, 1994, Liu et al., 2004).

Fuzzy set theory is used to enhance the ER to be FER. One of the most common fuzzy logic approaches is developed based on the fuzzy IF-THEN rules, where conditional parts, AND/OR, containing linguistic variables. FER can eliminate the "incompatible" belief degree distributions in traditional fuzzy rule-based IF-THEN risk assessment methods to implement the subjective vulnerability assessment rationally and visibly. Five assessment grades, which are enough to represent climate risk levels, are determined by using a fuzzy. Nevertheless, the risk levels of climate threats are also represented by several linguistic expressions.

AHP are the only two methods can perform weighting assignment. MAUT needs a lot of input and it is mainly used to represent the preferences of an agent over choices. Therefore, AHP is more suitable as the data collection for climate resilience is scalable.

Among the techniques that support decision making, the analytic hierarchy process (AHP) is the most often used and well known. Moreover, AHP is capable of solving multiple-criteria decision-making (MCDM) problems on sustainability and climate issues (Panjwani et al., 2019, Alburo et al., 2019, Dos Santos et al., 2019), which are strictly related to climate adaptation and resilience issues. Furthermore, fuzzy set theory is a common technique to be used alongside the AHP, and it occupies 28.32%. It has been implied in CCRI framework and CRI framework.

Prof. Thomas Saaty developed AHP in the 1970s, and the use of the AHP for decision making relies on a theory of relative measure based on the comparison between pairs used for standardized tables of absolute numbers whose elements are then used as priorities (Saaty, 1988). Also, decision making relies on a numerical scale for pairwise comparisons, which is crucial to compare the importance of two criteria. The AHP numerical scale varies from 1 to 9, where 1 indicates the equality of importance between two criteria, and 9 indicates that one activity is much more important than the others. Figure 2.9 presents the AHP's general hierarchical structure (Saaty, 1990).

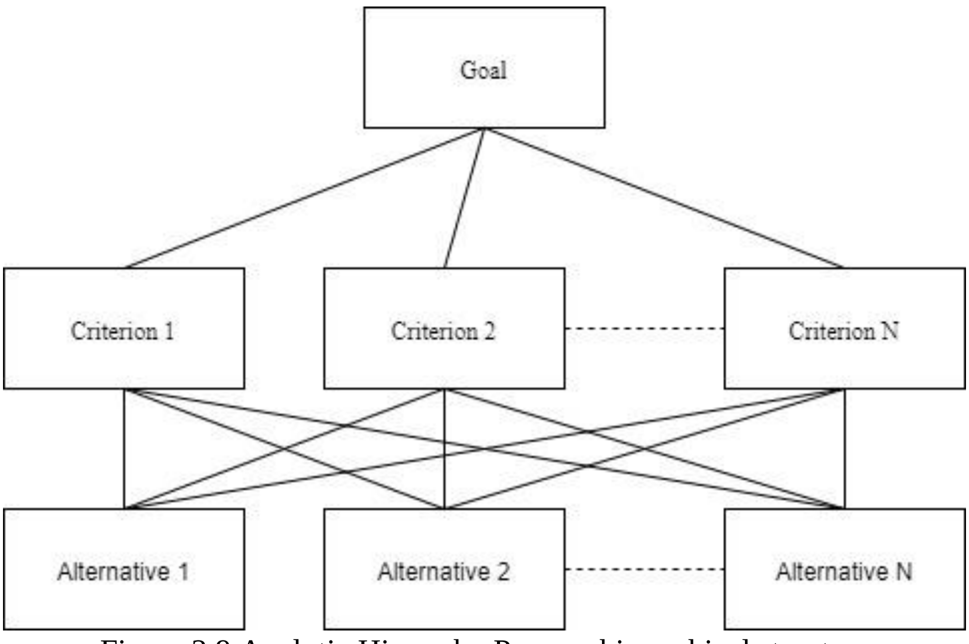

Figure 2.9 Analytic Hierarchy Process hierarchical structure

In this way, the decision-making process must be performed systematically and constructed in four steps (Saaty, 2008):

(1) Define the problem and determine the kind of knowledge sought;
(2) Structure the decision hierarchy from the top with the decision goal, then the objectives from a broad perspective, throughout the intermediate level (criteria on which subsequent elements depend) to the lowest level (which is usually a set of alternatives);
(3) Construct a set of pairwise comparison matrices. Each element in the upper level is used to compare the elements in the level immediately below it.
(4) Use the priorities obtained from the comparisons to weight the priorities in the level immediately below.

Then, repeat this for every element. Then, for each element in the level below, add its weight values and obtain its overall global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom-most level are obtained. For the realisation and analysis of judgments, the AHP works with decision square matrices with n orders and the eigenvectors related to them. Table 1 shows an example of the AHP, where the value, which is the estimate of the largest eigenvalue (λmax), has great importance since it can show the consistency degree of judgements. A matrix is consistent only if > n. To check the consistency of the comparisons matrix, a consistency index (ConI) is built. Also, an RI is a random index whose value varies according to the size of the pairwise comparison matrix. If ConI < 0.1, the comparison matrix will have an acceptable consistency. Otherwise, the judgement needs to be revised (Saaty, 1990) as shown in Table 2.4.

Table 2.5 Calculations to obtain the vector criteria

Criteria	***C1***	***C2***	***C3***	**Eigenvector**	**Criteria Vector (*W*)**
C_1	1	a_{12}	a_{13}		
C_2	$1/a_{12}$	1	a_{23}	$V_i = \prod_{i=1}^{n} a_{ij}^{\frac{1}{n}}$	$W_i = V_i / \sum V_i$
C_3	$1/a_{13}$	$1/a_{23}$	1		
Eigenvalue (λ_{max})	$\sum cji \times W_i$			$\sum V_i$	$\sum W_i$
Consistency ratio (ConR)	$(\lambda_{\max} - n)(n-1)/RI$				

Sources: (Dos Santos et al., 2019)

Chapter 3 Climate change risk indicator framework for seaports and airports

3.1. Summary

As there are different climate extremes and different adaptations for disasters, a platform to integrate all climate vulnerabilities is important to assess the climate vulnerabilities of transport infrastructures (e.g. seaports) in different seasons, now and in the future. Setting up a Climate Change Risk Indicator (CCRI) framework is a suitable method to tackle this issue. Also, the resources for climate change adaptation can be scientifically allocated for different seaports and airports against different climate threats in different seasons. Also, it is crucial to integrate all climate threats to compare the climate vulnerabilities across seaports by this platform, and thus to implement suitable adaptation measures to seaports.

This chapter first provides a critical review of climate change adaptation and vulnerability assessment for seaports and airports in Section 3.2. Also, the works of literature for implementing CCRI framework and the open data input are reviewed in the same section. Second, the CCRI assessment by the FER approach is explained step by step in Section 3.3. Third, seaports and airports in the UK are strategically selected to demonstrate the feasibility of the CCRI framework by the Fuzzy evidence reasoning approach in Section 3.4, followed by the research implications and conclusion in Section 3.5.

3.2. Review for Climate change risk indicators

The review consists of four types of documents, climate vulnerability assessments of seaports and airports, climate change adaptation reports, open climate data in the UK, and Fuzzy Evidence Reasoning (FER).

3.2.1. Review of climate vulnerability assessment on seaports

There are various studies for different climate vulnerabilities and increasing trends in climate change adaptation areas (Poo et al., 2018b). We observe a growing number of climate vulnerability studies for seaports and coastal regions. These two kinds of studies are closely related to the CCRI framework set-up and future development. By the literature review in Chapter 2, ten climate vulnerability impact studies have been conducted with a focus on seaports, and one climate vulnerability study examines different critical infrastructures. Here is the summary of the seaport studies in Table 3.1. There are different climate threats, and a method to encounter all different threats is not designed.

Table 3.1 Summary of climate vulnerability assessment for seaports

Location	Multi/ Single	Wind velocity/ direction	Storm surge	Wave height	SLR	Wave direction	Heat wave	Reference
Port Arthur, Tasmania	Single				v			(Hunter et al., 2003)
Port-aux-Francais, Kerguelen Island	Single				v			(Testut et al., 2006)
Rhine–Meuse–Scheldt delta	Multi		v	v	v			(Hua et al., 2012)
Port Kembla, New South Wales	Single				v			(Chhetri et al., 2015)
Catalan coast, North-west Mediterranean Sea	Multi	v		v	v			(Gracia et al., 2019, Sánchez-Arcilla et al., 2016, Sierra et al., 2016)
Northern Tyrrhenian Sea	Multi	v						(Repetto et al., 2017)
Port of Barcelona, Catalonia	Single			v	v	v		(Sierra et al., 2017b)
East Asian	Multi	v	v		v			(Lam et al., 2017)
Europe	Multi	v	v	v	v	v	v	(Forzieri et al., 2018)

Note: "v represents covered"

By analysing the eleven seaport climate vulnerability studies, climate threats are deemed as critical parameters for undergoing vulnerability assessments. “Wind velocity/ direction”, “Storm surge”, “Wave Height”, “Sea-level rise”, “Wave direction”, and “Heatwave” are the critical factors of climate vulnerability assessments, while “Temperature” and “Precipitation” are not mentioned in these eight studies. “Sea-level rise” is the most altered climate threat as it is included in all studies except the one by Repetto et al. in 2017, which is mainly focusing on wind events. “Sea-level rise” includes the assessments of sea-level changes with different scenarios and also defines the acceptable discharges of the seaports considered (Repetto et al., 2017). Forzieri et al. provide an assessment of different climate extremes on different critical infrastructures, including seaports and airports, in Europe. The findings from them will be used in the upcoming section for constructing the CCRI framework.

Multi-port and single-port studies both take place. Single-port studies focus on a vulnerability assessment for a seaport and give specific advice on adaptation and management. Multi-port studies assess the ports in a region for comparative analysis. By the review of climate vulnerability assessment in this section, different kinds of vulnerability have been visualized in Chapter 3. As there is without a platform to connect all climate threats, it shows the necessity to provide a CCRI framework for connecting different assessments.

3.2.2. Review of climate change adaptation reports

On 9th May 2011, the UK Government published Climate Resilient Infrastructure: Preparing for a Changing Climate (DEFRA, 2011). It sets out the Government's view on adapting infrastructures in transport sectors to the climate change impacts.

Table 3.2 Summary of climate risks to transport infrastructure

Infrastructure	Key risks
Roads	• Flooding from increased storminess and precipitation • Bridge destruction due to increased river flow resulting from storminess and precipitation • Road embankments damage in south-east England due to drier summers and wetter winters
Railways	• Flooding from increased storminess and precipitation • Bridge damage due to increased river flow resulting from storminess and precipitation • Rail embankments damage in south-east England due to drier summers and wetter winters • Overheating of underground trains by increased temperatures
Ports	• High tides / storm surges causing increased sea level at ports • High winds at ports due to increased storminess
Airports	• High winds at airports due to increased storminess

For the upcoming sections, climate change adaptation reports on seaports and airports are reviewed. First-round reports are submitted in 2011, and second-round reports are submitted in 2016. The risk items are listed in first-round reports, and they are verified again in the second-round reports. This section is important to gather all climate threats faced by the shipping authorities.

3.2.2.1. Review of seaport adaptation reports

DEFRA invited nine UK seaport professional bodies, and they submitted climate change adaptation reports about seaport risks under the Climate Change Act 2008. All reporting bodies are listed in Table 3.3.

Table 3.3 List of reporting seaports of climate change adaptation reports

Reporting bodies	Seaports/ Docks	Reference
Associated British Ports	Hull, Humber, Immingham and Southampton	(Associated British Ports, 2011)
Port of Dover	Dover	(Port of Dover, 2011)
Felixstowe Dock and Railway Company	Felixstowe	(Felixstowe Dock and Railway Company, 2011)
Harwich Haven Authority	Harwich Haven	(Jan Brooke Environmental Consultant Ltd, 2011)
Mersey Docks and Harbour Company Ltd	Liverpool	(Mersey Docks and Harbour Company Ltd, 2011)
Milford Haven Port Authority	Milford Haven	(Milford Haven Port Authority, 2011)
PD Teesport Ltd	Teesport and Hartlepool	(PD Teesport Ltd, 2011)
Port of London Authority	London	(Port of London Authority, 2011)
Port of Sheerness Ltd	Sheerness	(Peel Ports Group, 2011)

334 risk items have been addressed with different formats and scales. Even though the risk levels of each item cannot be directly compared, some insights can still be observed by statistical analyses by visualising the climate vulnerabilities in this century. Three sets of categories have been set up manually, including climate threat types, seasons, and operation sectors. As the Port of London Authority has not linked risk items to corresponding climate threats, 43 risk items from the Port of London have been excluded from the analyses in this study.

To define them on a standard plate, different climate threat types are reclassified with reference to the categories drawn up by the IPCC working group II in the Fifth Assessment Report of 2014, including “Extreme precipitation”, “Heatwave/ High temperature”, “Coldwave/ Increased snow events”, “Sea-level rise (SLR)/ Storm surge”, and “Storminess” (IPCC, 2014a). As some of the climate threats are yet threatening as serious as those in the above categories, they are defined as the climate concerns in this study. New climate concerns are found in adaptation reports mentioned in Table 3.4, including “Drought”, “Seasonal changes of fog events”, “Seasonal changes of lightning events”, “Seasonal changes of weather patterns”, and “Seasonal changes of wind speeds and directions”, “High water flow”, “Low water flow”, “Change in sediment”, and “High water temperature”. Climate threats are considered and classified, and each reported climate risk item can consist of more than one threat. For example, the Port of Dover has stated a threat, “Extreme conditions leading to staff absence, extra work and excess passengers cause staff to take time away from their core roles”. This threat is double-counted and reclassified as “Extreme precipitation”, and also “Coldwave/ Increase in winter precipitation”. “Storminess”, “Seasonal changes to wind speed and direction”, and “Extreme precipitation” play the three most important roles in affecting the operational activities of seaports with their individual occupancy rates larger than 30%. “Heatwave/ High temperature” and “Sea-level rise (SLR)/ Storm surge” are both crucial as they have their individual occupancy rate larger than 20%. The remaining threats/concerns, “Coldwave/ Increase in snow events”, “Drought”, “Seasonal changes of fog events”, “High water flow”, “Low water flow”, “Change in sediment”, and “High water temperature”, have their occupancies between 10% and 20% ,as seen in Table 3.4. Occupancy is the parameter used to measure the amounts of different categories against the total. For example, 88 risk items have been categorised as “Extreme precipitation” with an occupancy rate at 30.24% (88/(334-43[1])).

Table 3.4 Occupancy of different climate threats for seaports

Climate concerns	**Occupancy**	**Example**
Extreme precipitation	88 (30.24%)	“Contamination of potable water service caused by flooding.”
Heatwave/ High temperature	78 (26.80%)	“Inadequacy of air-conditioning causing discomfort and sub-optimal working conditions.”
Coldwave/ Increase in snow events	51 (17.53%)	“Fracture risk to underground infrastructure from increased winter temperature variability and freeze / thaw damage.”
Sea-level rise (SLR)/ Storm surge	77 (26.46%)	“Damage to site infrastructure/the river/surrounding environment if flooding results in pollution incidents.”
Storminess	112 (38.49%)	“Increase in storm damage and corrosion.”
Drought	32 (11.00%)	“A shortage of water supply.”
Seasonal changes of fog events	43 (14.78%)	“Increased delays in mooring/pilot transfer/vessel movements”
Seasonal changes to wind speed and direction	97 (33.33%)	“Reducing usability of lift bridge.”
High water flow	37 (12.71%)	“Changes in distribution of bird populations and/or migratory patterns”

[1] Here 334 is the total risk items while 34 means the number of risk terms from Port of London, which have not been categorised into any climate threats as explained above.

Low water flow	33 (11.34%)	"Uncontrolled opening of gates affecting loading/ unloading."
Change in sediment	32 (11.68%)	"Potential greater wear on components in contact with water."
High water temperature	38 (13.06%)	"Potential reduction in engine efficiency due to less efficient cooling."

Table 3.5 Occupancy of climate risks in different seasons for seaports

Season	Winter	Summer	Annual
Occupancy	29 (9.97%)	59 (20.27%)	203 (69.76%)

In Table 3.5, we can observe that summer poses more risk than winter, and about 70% of the climate threats are not seasonal. In Table 3.6, 334 risk items (including the 43 from the Port of London) are all included, and operation sectors are based on the definitions from Harwich Haven Authority. "Approaching routes connectivity" describes the possibilities of road/rail closure due to adverse weather. "Snow and flooding" also affects the stability of the road and rail infrastructures. "Civil engineering, jetties, pontoons" describes the risk of poor designs, jetties being submerged by extreme events, especially SLR. "Electrical engineering/ Power supplies" states the risks by flooding water to any electrical infrastructure causing power outage. "External reputation" describes the possibilities of losing the external reputation due to delay and cancellation of services. "Hydrography and dredging" describes the risk coming with the change in coastal lines and disruptions to hydrographic surveying and dredging regime. "Increase in tourism and recreational use" can cause the busy traffic and activities near ports or the port routes which can enhance risks. "Infrastructure and equipment" describes the risks in adverse weathers damaging the coastal infrastructure and equipment, which include tarmac, ramps, and cranes. "Licensing and consenting" stated the chance of insurance premiums rising because of the unstable services. "Freight loading and moving" talked about effects and delays in cargo movements. "Marine engineering" stated the risks inside the vessel, mainly potential reduction. "Navigation" described the effect on navigational safety of inadequate Nav-aids, buoys and height of beacons. "Staff and personnel/ Business continuity" are mainly about operating conditions for staff in different areas. "Statutory duties" describes the regulatory issues, such as the increasing spread of invasive alien species and sea defence adversely impact. "Storage and cargos" may have a higher risk for different kinds of cargos by the increase in EWEs. "Vessel services" states the disruptions of vessel movements on the water. "General" defines risk items without specific operation sectors. "Infrastructure and equipment", "Vessel services", and "Staff and personnel/ Business continuity" are the three most affected operation sectors. The fact is understandable as they are more climate-sensitive compared to civil and electrical engineering sectors.

Table 3.6 Occupancy of different operation sectors for seaports

Operation sector	**Occupancy**	**Example**
Approach routes closure	7 (2.10%)	"Snow and ice preventing employees getting to work."
Civil engineering, jetties, pontoons	5 (1.50%)	"If frequency and severity of EE increased, pontoon and jetty designs may prove inadequate."
Electrical engineering/ Power supplies	14 (4.19%)	"Power supplies disrupted owing to off-site disruption to the network."
External reputation	6 (1.80%)	"Reputation of port operator damaged."
General	15 (4.49%)	"Port closure."
Hydrography and dredging	23 (6.89%)	"Disruption to hydrographic surveying regime and dredging regime."
Increase in tourism and recreational use	7 (2.10%)	"Increase in leisure activity."
Infrastructure and equipment	64 (19.16%)	"Tarmac broken through heat softening."
Licensing and consenting	15 (4.49%)	"More Insurance claims to cover effects."
Loading and moving	29 (8.86%)	"Uncontrolled opening of gates affecting loading/ unloading."
Maintenance dredging and disposal	3 (0.90%)	"Changes in sedimentation could lead to changes in dredging requirements."
Marine engineering	7 (2.10%)	"Increased growth of marine organisms (hull fouling; algal blooms, etc. drawn into cooling system)."
Navigation	17 (5.09%)	"Mooring inadequate to maintain buoy position."
Staff and personnel/ Business continuity	32 (9.58%)	"Increased office temperature affecting working conditions."
Statutory duties	27 (8.08%)	"New development design and specifications need to take account of climate change projections and monitor trends."
Storage and cargos	25 (7.49%)	"Damage/degradation of stored vehicles from high temperature/storage in direct sunlight."
Vessel services	37 (11.38%)	"Extreme cold/ice, heavy rain leading to increased hazards and increased downtime"

3.2.2.2. Review of airport adaptation reports

Apart from seaports, nine UK airport reporting bodies mentioned in Table 3.7 were invited by the UK DEFRA and they submitted climate change adaptation reports about airport risks under the Climate Change Act 2008:

Table 3.7 List of reporting airports of climate change adaptation reports

Reporting bodies	Airports	References
Birmingham Airport Holdings Ltd.	Birmingham Airport (BHX)	(Birmingham Airport Holdings Ltd, 2011)
Abertis Infraestructuras, S.A.	Cardiff Airport (CWL)	(Abertis Infraestructuras S.A., 2011)
Edinburgh Airport Ltd.	Edinburgh Airport (EDI)	(Edinburgh Airport Ltd., 2011)
Gatwick Airport Ltd.	Gatwick airport (LGW)	(Gatwick Airport Ltd., 2011)
Glasgow Airport Ltd.	Glasgow Airport (GLA)	(Maclachlan, 2011)
Heathrow Airport Ltd.	Heathrow Airport (LHR)	(Heathrow Airport Limited, 2011)
London Luton Airport Ltd.	London Luton Airport (LTN)	(London Luton Airport Ltd., 2011)
Manchester Airports Group plc. (MAG)	Manchester Airport (MAN) And East Midlands Airport (EMA)	(Manchester Airports Group plc, 2011)
BAA Airports Ltd.	London Stansted Airport (STN)	(Jefferson, 2011)

Except for EDI, the other eight airports have implemented risk assessments. 207 risk items have been addressed with different formats and scales. Even though the risk levels of each item cannot be directly compared, some insights can still be observed by statistical analyses by visualising the climate vulnerabilities in this century. Three sets of categories have been set up manually, including climate threat types, seasons, and operation sectors.

To define them on a standard plate, different climate threat types are reclassified with reference to the categories drawn up by the IPCC working group II in the Fifth Assessment Report of 2014, including “Extreme precipitation”, “Heatwave/ High temperature”, “Cold wave/ Increased snow events”, “Sea-level rise (SLR)/ Storm surge”, and “Storminess” (IPCC, 2014a). As some of the climate threats are yet threatening as serious as those in the above categories, they are defined as the climate concerns in this study. New climate concerns are found in adaptation reports mentioned in Table 4.2, including “Drought”, “Seasonal changes of fog events”, “Seasonal changes of lightning events”, “Seasonal changes of weather patterns”, and “Seasonal changes of wind speeds and directions”. Climate threats are considered and classified, and each reported climate risk item can consist of more than one threat. For example, STN has stated a threat, “Increased energy demand for cooling in the summer, and for heating during winter extremes increases energy spend and emissions. High temperatures reduce performance of some plant”. This threat is double-counted and reclassified as “Heatwave/ High temperature”, and also “Coldwave/ Increase in winter precipitation”. Occupancy is the parameter used to measure the amounts of different categories against the total. For example, 88 risk items have been categorised as “Extreme precipitation” with an occupancy rate at 13.53% (28/207).

Table 3.8 shows the occupancy distribution of different climate threats. “Heatwave/ High temperature” plays the most important role in affecting the operational activities of airports with their individual occupancy rates larger than 44%. “Cold wave/ Increase in snow events” is the second most important and it is more than 22%. The remaining threats/concerns have their occupancies between 11% and 15%.

Table 3.8 Occupancy of different climate threats for airports

Climate threat	**Occupancy**	**Example**
Extreme precipitation	28 (13.53%)	“Changes to clay soils on which the Airport is built during warmer, drier summers and increased variance between summer and winter water levels”
Heatwave/ High temperature	93 (44.93%)	“Increased energy demand for cooling in the summer, and for heating during winter extremes increases energy spend and emissions. High temperatures reduce performance of some plant.”
Coldwave/ Increase in snow events	47 (22.71%)	“Fracture risk to underground infrastructure from increased winter temperature variability and freeze / thaw damage.”
Sea-level rise (SLR)/ Storm surge	27 (13.04%)	“SLR / storm surge risks disruption to UK infrastructure i.e. utility supplies, surface transport routes (without adaptation).”
Storminess	30 (14.49%)	“Increased longevity of wing tip vortex effect due to general becalming of surface wind speeds.”
Drought	29 (14.01%)	“Drought conditions affect water availability. Restrictions may be posed to water intensive activities.”
Pollution	23 (11.11%)	“Increase in local air quality pollutants, such as ozone”
Seasonal changes of fog events	24 (11.59%)	“Seasonal changes to fog related disruption”
Seasonal changes of lighting events	36 (17.39%)	“Impacts of lightning on control systems and electricity supply. Power cuts and voltage spikes to parts of the airport not on UPS during electrical storms.”
Seasonal changes to weather pattern	27 (13.04%)	“Changes in distribution of bird populations and/or migratory patterns”
Seasonal changes to wind speed and direction	28 (13.53%)	“Increased longevity of wing tip vortex effect due to general becalming of surface wind speeds.”

Table 3.9 Occupancy of climate risks in different seasons for airports

Season	**Winter**	**Summer**	**Annual**

Occupancy	67 (16.43%)	34 (32.37%)	106 (51.21%)

In Table 3.9, we can observe that summer poses more risk than winter, and more than half of the climate threats are not seasonal. On the other hand, we can divide the airport infrastructure and its operational activities into different risk categories based on the definition of the Airport Council International (Airport Council Internation, 2018): "Airfield (including Runways, Taxiways and Aprons)", "Terminals and Landside Infrastructure", "Support Facilities, Navigational Aids, Fuel Storage, and Others", "Aircraft Operation", "Air/Ground Navigation Control", "Wildlife Hazard Management", "Other Operational Aspects", "Environment Management", and "Personnel and Passengers". After categorising risk items by different infrastructure and types, some of the items cannot fit in as they are about difficulties in climate forecasting or increase in insurance cost. So, "Technical standards and assurance" is chosen from the Heathrow Airport climate adaptation report for analysis (Heathrow Airport Limited, 2011).

"Airfield (including runways, taxiways, and aprons)" considers deterioration and contamination on the airfield. Besides, drainage and electrical system on the airside are included. "Terminals and Landside Infrastructure" considers impedance of surface access, damage to terminals, and undermined ground foundations. "Support Facilities, Navigational Aids, Fuel Storage, and Others" includes facilities damage and a corresponding increase in maintenance. Electrical system failure and fire risk are more significant which require more consideration. "Aircraft Operation" considers the decrease of lift and reduction of the rate of climb of planes at the higher temperature. Also, there may be changes in wind direction. As there are possibilities for aircraft to encounter extreme weathers, so more maintenance, repair, and overhaul are required. Visibility reduction affects air transport safety and the levels of communications system failure increase in "Air/Ground Navigation Control". "Wildlife Hazard Management" includes changes in ecosystems and distributions of wildlife and wildlife attractants and the corresponding increase of wildlife strikes. "Emergency Management" contains weather-related emergencies and use of the airport as shelter or as a hub for relief operations. "Other Operational Aspects" includes water shortage, increase in energy demand of air conditioning, and delays and flight cancellation. "Environment Management" consists of changes in noise emission pattern and increased complaints, changes in ecosystems and associated risks, and reduction in air quality. "Personnel and Passengers" includes the risk of heat-related exhaustion of staff, changes in tourism patterns, and risks of communicable diseases and epidemics. “Technical standards and assurance” includes the documentary and insurance issues.

Table 3.10 describes the risks distributed in different parts of airports. From the infrastructure side, “Airfield (including Runways, Taxiways and Aprons)”, “Terminals and Landside Infrastructure”, and “Support Facilities, Navigational Aids, Fuel Storage, and Others” occupy 20.77%, 15.46%, and 15.94% occupancies respectively. So, risks are distributed in different areas of airports, and further investigations can be done separately for different areas. From the operation perspective, “Aircraft Operation”, “Other Operational Aspects”, and “Personnel and Passengers” occupy 14.98%, 14.01%, and 12.56% occupancies respectively. “Aircraft Operation” has the highest occupancy because of the potential lower take-off performance and the other climate risks such as affecting the airside. “Other Operational Aspects” has a great percentage because every airport recognises flight interruption and increase in energy demand. “Personnel and Passengers” occupies a significant percentage because more extreme weathers affect the travel patterns of passengers. Also, the working conditions at the airport are worsening. “Environment Management” is the fourth largest sector because there are increases in disease vectors and local air pollutants. “Air/Ground Navigation Control”, “Wildlife Hazard Management”, and “Technical standards and assurance” take part in small proportions also. “Emergency Management” is the only category without any risk items fitting in. It is because this category is about the use of an airport as a shelter or relief hub for weather-related disasters. Some risk items are considered as infrastructure risk and also operation risk.

Table 3.10 Occupancy of different infrastructure and operation suffering from climate risks

Category	**Occupancy**	**Example**
Infrastructure		
Airfield (including Runways, Taxiways and Aprons)	43 (20.77%)	“Airfield surface and sub-surface structural damage to runway and aprons from extreme heat.”
Terminals and Landside Infrastructure	32 (15.46%)	“Overheating of operationally-critical buildings which could impair performance of critical staff or equipment and breach regulated conditions.”
Support Facilities, Navigational Aids, Fuel Storage, and Others	31 (15.94%)	“Flashpoint of aviation fuel exceeded on hot days - potential fire hazard.”
Operation		
Aircraft Operation	31 (14.98%)	“Longer aircraft take-off run due to 'thin air' and reduced aircraft engine efficiency.”

Air/Ground Navigation Control	8 (3.86%)	"Impacts of lighting on control systems and electricity supply. Power cuts and voltage spikes to parts of the airport not on UPS during electrical storms."
Wildlife Hazard Management	7 (3.38%)	"Change in distribution of pests and wildlife species. Potential changes to bird migration patterns and bird strike risk."
Emergency Management	0 (0%)	N/A
Other Operational Aspects	29 (14.01%)	"Increased energy demand for cooling in the summer, and for heating during winter extremes increases energy spend and emissions. High temperatures reduce performance of some plant."
Environment Management	20 (9.66%)	"More residents' windows open, particularly at night, leading to greater propensity to complain
Personnel and Passengers	26 (12.56%)	"SLR / storm surge risks disruption to UK infrastructure i.e. utility supplies, surface transport routes (without adaptation)."
Technical standards and assurance	3 (1.45%)	"Increased insurance costs."

3.2.3. Review of open climate data in the United Kingdom

The data relating to CCRIs for observing and analysing climate threats are obtained from multiple data sources including the Meteorological Office (Met Office, 2018), Climate Projection (UK Climate Projection, 2018), and British Oceanographic Data Centre (BODC) (British Oceanographic Data Centre, 2018). They are all open data available from the associated websites.

Met Office is the United Kingdom's national weather service. It is an executive agency and of the Department for Business, Energy and Industrial Strategy. They forecast the climate change across all timescales from weather forecasts. In 2009, UK Climate Projections in 2009 (UKCP09) is released, and it provides a data assessment of how the UK climate may change in this century. UKCP09 is a gridded observation dataset. The historical dataset spans across the period of 1910–2016 and covers the UK at a 5 x 5 km resolution. The data from 2016 – 2019 have been checked without a huge change. Therefore, it is used to observe the current risks and set up the grades of the CCRIs for analysis. The future dataset is in the same format and it is possible to foresee the future climate risk levels by the same framework. The definitions and timeframes of climate indices are shown in Table 3.11.

Table 3.11 Definition and timeframe of Climate change risk indicators from Met Office

Climate index	Definition	Timeframe
Maximum temperature	Average daily maximum air temperature (oC)	1910 – 2016
Minimum temperature	Average daily minimum air temperature (oC)	1910 – 2016
Precipitation	Total precipitation amount (mm)	1910 – 2016
Mean wind speed	Average hourly mean wind speed at a height of 10 m above ground level (knots)	1969 – 2014
Mean sea level pressure	Average hourly mean sea level pressure (hPa)	1961 – 2014
Mean relative humidity	Average hourly relative humidity (%)	1961 – 2014
Mean vapour pressure	Average hourly vapour pressure (hPa)	1961 – 2014
Mean cloud cover	Average ourly total cloud cover (%)	1961 – 2006
Days of air frost	Counted days when the minimum air temperature is below 0 oC (days)	1961 – 2016
Days of ground frost	Counted days when the grass minimum temperature is below 0 oC (days)	1961 – 2016
Days of rain >= 10 mm	Counted days with >= 10mm precipitation (0900-0900 UTC) (days)	1961 – 2016
Days of sleet or snow falling	Counted days with sleet or snow falling (days)	1971 – 2011

Then, ten maximum sea-level records and ten maximum skew surge records are collected from 45 UK seaports from BODC. BODC is a national facility for collecting and releasing data about the marine environment for the UK and it is a part of the National Oceanography Centre (NOC). It is for observing the risks of flooding due to SLR. Average values of two types of the top-ten records have been calculated for each seaport. As some of the airports in the UK are built by the coast, Aberdeen International Airport (ABZ) is one of the coastal airports which has been chosen to be evaluated in the study. Each airport is evaluated by the seaport data which is away from the airport by not more than 10 miles. Based on our rank-ordered statistics any extreme storm surge can coincide with any tide, therefore skew surge which is the difference between the maximum observed sea level and the maximum predicted tide are used as an indicator (Williams et al., 2016). The maximum observed sea level measured by tide gauges are primarily determined by the tidal regime. The difference (residual) between the maximum observed sea level and the maximum predicted tide is governed by the wind stress and the local atmospheric pressure, roughly two thirds to one third split, respectively.

3.3. Formulation of the Climate change risk indicator framework

By connecting all input information and undertaking analysis, it is possible to convert different types of CCRIs into a climate risk index. The following equations have integrated the newest ER algorithm within the CCRI context. A represents the set with five linguistic assessment grades {L1 "Low risk", L2 "Moderately low risk", L3 "Medium risk", L4 "Moderately high risk", L5 "High risk"}, which has been combined from two subsets A_1 and A_2 based on two different CCRIs. Let α represent degrees of belief attaching to different linguistic terms and ω represent the normalised relative weights of the two CCRIs.

$$A = \{\alpha_1 L_1, \alpha_2 L_2, \alpha_3 L_3, \alpha_4 L_4, \alpha_5 L_5\}, \text{ where} \sum_{m=1}^{5} \alpha_m \le 1 \tag{3.1}$$

$$A_k = \{\alpha_{1,k} L_1, \alpha_{2,k} L_2, \alpha_{3,k} L_3, \alpha_{4,k} L_4, \alpha_{5,k} L_5\}, \text{ where} \sum_{m=1}^{5} \alpha_{m,k} \le 1 \text{ and } k = 1, 2 \tag{3.2}$$

$$\sum_{k=1}^{2} \omega_k = 1 \tag{3.3}$$

$$M_{m,k} = \omega_1 \alpha_{m,k}, \text{ where m = 1, 2, 3, 4, 5 and k = 1, 2} \tag{3.4}$$

Equation (3.1) represents the set with five linguistic assessment grades and Equation (3.2) represents the corresponding CCRIs fuzzy sets from two subsets. By the total normalised relative weights given in Equation (3.3), and individual relative weight obtained, the individual degrees, M can be obtained by Equation (3.4).

$$H_k = \bar{H}_k + \tilde{H}_k, \text{ where k = 1, 2} \tag{3.5}$$

$$\bar{H}_k = 1 - \omega_k, \text{ where k = 1, 2} \tag{3.6}$$

$$\tilde{H}_k = \omega_k \left(1 - \sum_{m=1}^{5} \alpha_{m,k}\right), \text{ where k = 1, 2} \tag{3.7}$$

Equations (3.5) to (3.7) represent the remaining belief values (H) unassigned for $M_{m,1}$ and $M_{m,2}$, where m = 1, 2, 3, 4, 5. $\bar{H}$ represents the degree to which other CCRI can play a role in the assessment and $\tilde{H}$ is attributable to the possible incompleteness in the subsets A_1 and A_2.

$$a'_m = K\left(M_{m,1} M_{m,2} + M_{m,1} H_2 + H_1 M_{m,2}\right), \text{ where m = 1, 2, 3, 4, 5} \tag{3.8}$$

$$\bar{H}'_U = K\left(\bar{H}_1 \bar{H}_2\right) \tag{3.9}$$

$$K = \left(1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} M_{T,1} M_{R,2}\right)^{-1} \tag{3.10}$$

Let a'_m be the non-normalized degree to which the synthesised evaluation is confirmed to the five linguistic grades and $\bar{H}'_U$ the non-normalised remaining belief unassigned after the commitment of belief to the five linguistic grades. They work together as the result of the synthesis of the risk degrees. After the above 10 equations, the final two equations mean the calculation of the combined degrees a_m. They are generated by putting $\bar{H}'_U$ back to the five expressions using the following normalisation process and H_U means the normalised remaining belief unassigned in the synthesised set.

$$a_m = a'_m / \left(1 - \bar{H}'_U\right), \text{ where m = 1, 2, 3, 4, 5} \tag{3.11}$$

$$H_U = \tilde{H}_U / \left(1 - \bar{H}'_U\right) \tag{3.12}$$

The above equations give the process of combining two CCRI fuzzy sets. If three CCRI fuzzy sets are required to be combined, the result obtained from the combination of any two sets can be further synthesised with the third one using the above algorithm. Similarly, multiple sets from the evaluations of more sub-criteria or the judgements from multiple persons can also be combined. The application of the approach, however, requires the assumption that all evaluations are assessed or obtained based on the same linguistic expressions. However, some criteria are with different linguistic expressions. In order to unify the linguistic terms associated with different sets of assessment grades, a knowledge-based fuzzy mapping technique is presented here using belief distribution-based utility theory (Yang et al., 2009).

3.4. Climate change risk indicator assessment by the Fuzzy evidence reasoning approach

Task Team on Definitions of Extreme Weather and Climate Events (TT-DEWCE) from the World Meteorological Organization (WMO) has stated that there are fixed and well known extreme events and their thresholds differ from location to location (TT-DEWCE, 2016). For comparing different ports' climate characteristics, the climate data across the whole UK is collected, and then assessment grades are defined by obtaining specific percentiles (Zanobetti et al., 2013). The climate data of seaports are chosen and evaluated from the lowest level to the highest-level criteria in a developed hierarchy in Section 3.3.1. Next, all evaluations are synthesized using the formulations in Section 3.3.

3.4.1. Step 1: Defining the Climate change risk indicator hierarchy

By gathering data from the Met Office, the UK Environment Agency, and BODC, we summarise the CCRI hierarchy in Table 3.11. 5 x 5 km monthly gridded observational datasets and 25 x 25 km monthly gridded forecasting datasets are collected from UKCP09, and we can find some forecasting data to compare the existing and future risks. Climate threats are linked to EWEs with the reference of literature review, and EWEs are linked to CCRIs with the MET office analysis and expert review. The future period is set to be 2050s (2040-2069), and the emission scenario is defined as medium. 50th percentile data in the 2050s with a medium emission scenario is taken as the reference for analysis as they had made a probabilistic projection for every variable. 2050 is a key year recommended for reaching global net zero CO2 emissions by the IPCC, and so it is commonly used for a forecasting reference (Owen et al., 2010).

The findings on climate threats in Table 3.4 and Table 3.8 partially match the finding from the IPCC working group II in 2014. Climate-related drivers of impacts to urban areas are chosen, and they include “Warming Trend”, “Extreme temperature”, Drying trend”, Extreme precipitation, “Snow cover”, “Damaging cyclone”, and “Sea-level rise”. As “Warming Trend”, “Extreme temperature”, and “Drying trend” always come together in the adaptation reports, therefore, they have been merged into “Warming trend/ Extreme temperature/ Drought”.

However, some climate concerns mentioned do not have enough open climate data to access, and the climate concerns harm the seaports and airports with different scales. From Table 3.1, there is no existing framework suitable for this assessment. Thus, some climate threats are classified with two references from the IPCC working group II in 2014 and Forzieri et al. (Forzieri et al., 2018). Then, open climate data collected for assessing the risk levels of climate threats are shown in Table 3.11. Nevertheless, climate threats and corresponding EWEs identified in this section are chosen, as mentioned in Table 3.12, for assessing climate exposure of airports by CCRI framework for assessing climate vulnerabilities of seaports and airports.

Table 3.12 Occupancy of different operation sectors

Climate threat	EWE
Warming trend/ Extreme temperature/ Drought	Heatwave / Drought/ Wildfires
Extreme precipitation	Flooding
Snow cover	Cold wave/ Snow events
Damaging cyclone	Wind gust/ Storminess
Sea-level rise	Flooding

Heat stress is projected to increase by many climate model ensembles and generations, driven mainly by temperature increases, humidity declines and low cloud cover (Stefanon et al., 2012). Therefore, "Warming trend/ Extreme temperature/ Drought" is defined by combining the warming and drying trend, and the whole framework is shown in Table 3.13 and Figure 3.1. Further explanation of each index is shown in Annex 1.

Table 3.13 Summary of Climate Change risk indicator framework

Climate threat	EWE	CCRI	UB/ LB	Source	Monthly data	Forecast data
Warming trend/ Extreme temperature/ Drought	Heatwave Drought Wildfires	Maximum temperature (^{o}C)	UB	Met Office	Yes	Yes
		Relative humidity (%)	LB	Met Office	Yes	Yes
		Rainfall (mm)	LB	Met Office	Yes	Yes
		Cloud cover (%)	LB	Met Office	Yes	Yes
Extreme precipitation	Flooding	Rainfall (mm)	UB	Met Office	Yes	Yes
		Days of rain >= 10.0 mm (days)	UB	Met Office	Yes	No
Snow cover	Coldwave/ Snow events	Days of air frost (days)	UB	Met Office	Yes	No
		Days of ground frost (days)	UB	Met Office	Yes	No
		Days of sleet and snow falling (days)	UB	Met Office	Yes	No
		Days of snow lying (days)	UB	Met Office	Yes	No
		Minimum temperature (^{o}C)	LB	Met Office	Yes	Yes
Damaging cyclone	Wind gust/ Storminess	Rainfall (mm)	UB	Met Office	Yes	Yes
		Vapour pressure (hPa)	LB	Met Office	Yes	No
		Mean seal level pressure (hPa)	LB	Met Office	Yes	Yes

		Mean wind speed (knots)	UB	Met Office	Yes	Yes
Sea-level rise	Flooding	Maximum relative sea level record (m)	N/A	BODC/ Met Office	No	Yes
		Maximum skew surge record (m)	N/A	BODC/ Met Office	No	Yes

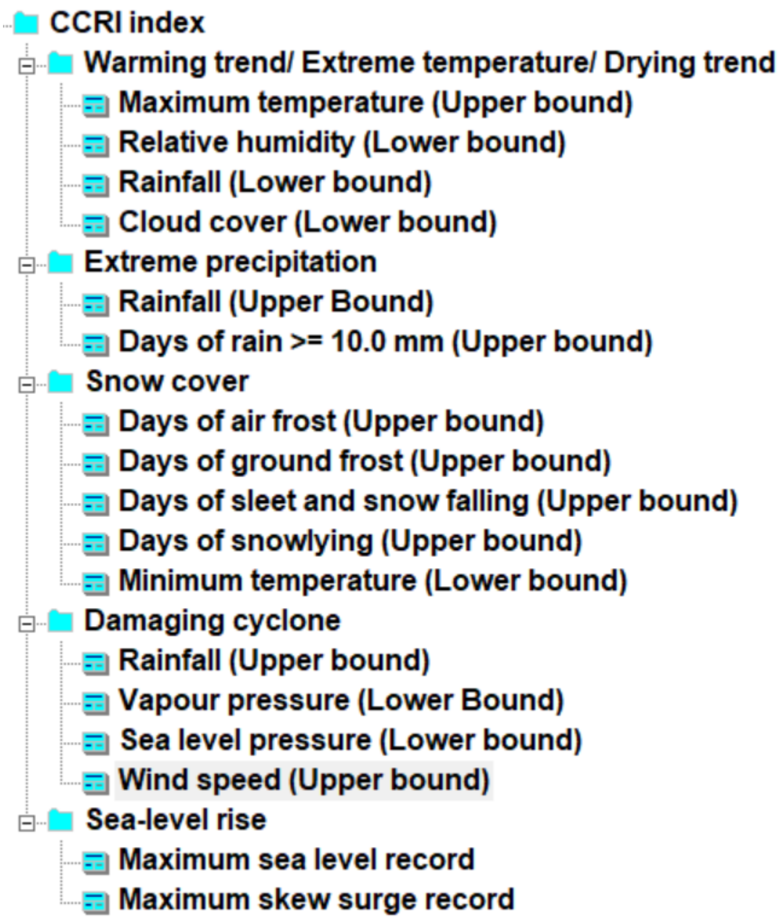

Figure 3.1 Climate change risk indicator framework

3.4.2. Step 2: Setting the criterion grades

After selecting the indicators, the next step is grading the data. Percentile values are commonly used in assessing and grading the climate vulnerability by climate data (Peterson et al., 2002, Monahan and Fisichelli, 2014). By consulting the professions shown in Table 3.14 from maritime industry and environmental science, percentile values of different data are chosen and the dataset for CCRI framework is set up. Profession of them can be defined in academic, airline, airport management, shipping agent, and seaport management. Airports are also set up for cross reference in the section. Therefore, the related consultations are shown.

Table 3.14 Profession background

ID	Profession	Years of experience
1	Academic	12
2	Academic	10
3	Academic	23
4	Airline	5
5	Airport management	14
7	Airport management	4
8	Shipping agent	5
9	Shipping agent	6
10	Seaport management	4

Extreme values can be defined by obtaining extreme percentile ranks. From the Met Office, 5 x 5 km monthly gridded observational datasets of the whole United Kingdom are collected. Then, 60th, 70th, 80th, 90th and 95th percentile values are used to divide the upper bound (UB) assessment grades into five categories, and 40th, 30th, 20th, 10th and 5th percentile values are used to classify the lower bound (LB) assessment grades. UB and LB of "Rainfall" both exists in the framework because they are used in different climate threats, "Warming trend/ Extreme temperature/ Drought" and "Extreme precipitation". All datasets can fit the set with five linguistic assessment grades {L1 "Low risk", L2 "Moderately low risk", L3 "Medium risk", L4 "Moderately high risk", L5 "High risk"}, which are explained in Section 3. Based on the classification of disaster types on critical infrastructure stated by Forzieri et al. (2018), climate variables are categorised, and the values used as defining grades are shown in Table 3.15.

Table 3.15 Marginal values of Climate change risk indicators from Meteorological Office for defining grades

Climate threats	CCRI	LB/ UB	Grade (Percentile) L_1 40^{th}/ 60^{th}	L_2 30^{th}/ 70^{th}	L_3 20^{th}/ 80^{th}	L_4 10^{th}/ 90^{th}	L_5 5^{th}/ 95^{th}
Warming trend/ Extreme temperature/ Drought	Maximum temperature (°C)	UB	13.73	15.5	17.24	19.17	20.52
	Relative humidity (%)	LB	81.52	78.54	78.54	76.31	74.47
	Rainfall (mm)	LB	62.22	51.09	40	27.05	18.59
	Cloud cover (%)	LB	69.96	67.76	64.9	60.64	56.71
Extreme precipitation	Rainfall (mm)	UB	88.5	105.94	130.5	174.68	222.65
	Days of rain >= 10.0 mm (days)	UB	2.62	3.31	4.38	6.24	8.22
Snow cover	Days of air frost (days)	UB	3.64	6.12	9.15	13.52	17.17
	Days of ground frost (days)	UB	11.09	14.03	16.88	20.38	23.06

	Days of sleet and snow falling (days)	UB	0.68	1.78	3.4	6.3	9.17
	Days of snow lying (days)	UB	0.04	0.39	1.53	4.37	8.01
	Minimum temperature (^{o}C)	LB	6.22	7.75	9.2	10.59	11.48
Damaging cyclone	Rainfall (mm)	UB	88.5	105.94	130.5	174.68	222.65
	Vapour pressure (hPa)	LB	8.32	7.78	7.26	6.63	6.14
	Mean sea level pressure (hPa)	LB	1012.73	1011.21	1009.21	1006.02	1003.08
	Mean wind speed (knots)	UB	9.92	10.88	12.2	14.36	16.44

The maximum sea level records and maximum skew surge records from the National Tidal and Sea Level Facility are presented by extreme data which is different from Met office's ordinate climate data. To associate such extreme data with the defined five grades (i.e. "Low vulnerability", "Moderately low vulnerability", "Medium vulnerability", "Moderately high vulnerability", "High vulnerability") a linear distribution of records from all 45 ports is developed based on 10th, 30th, 50th, 70th, and 90th percentiles as presenting in Table 3.16 (Zhang et al., 2013). For forecasting, we used the UKCP09 values, the long-term linear trend in the skew surge (1951-2099) for the return level of 10 years (mm/yr) and sea-level change (m), to foresee the sea-level and storm surge changes. If the airport is not constructed by coast, the two CCRIs from BODC are graded as "Low vulnerability".

Table 3.16 Marginal values of Climate change risk indicators from British Oceanographic Data Centre for defining grades

	Grade (Percentile)				
CCRI	**10th**	**30th**	**50th**	**70th**	**90th**
Maximum sea level record (m)	2.31	3.02	3.44	4.02	6.10
Maximum skew surge record (m)	0.69	0.81	0.95	1.14	1.39

3.4.3. Step 3: Evaluating seaports and airports using climate data

The input datasets, now and future, are used to evaluate seaports using climate data from the lowest level of the CCRI framework. Twelve seaport groups mentioned in Table 3.3, "Dover (DOV)", "Dundee (DUN)", "Felixstowe (FEL)", "Grangemouth (GRA)", "Immingham (IMM)", "Leigh (LEI)", "Liverpool (LIV)", "London (LON)", "Milford Haven (MIH)", "Sheerness (SHE)", "Southampton (SOU)", and "Tee (TEE)", are chosen for a demonstration as they are near different urban areas and they are mostly assigned by the UK government to implement an adaptation plan.

For the airport selection, ten airport reporting bodies mentioned in Table 3.7, invited for submitting climate change adaptation reports about airport risks under the Climate Change Act 2008 are chosen to be evaluated. Also, ABZ is chosen too as it is serving an urban area in the north, and it is a top ten busiest airport in the UK for both passengers and freight.

3.4.4. Step 4: Transforming the evaluation from the lowest level to top-level criteria

The CCRI framework consists of three layers: “Climate risk index”, “Climate threats”, and “CCRIs”. The relative weights are also necessary for connecting three layers as mentioned in Section 3.4.1. For “CCRIs”, all CCRIs have equal weights and the weight assignment is done on the second level, “Climate threats”. For “Climate threats”, the weight assignment come from a sensitivity study for different seaports in Europe (Forzieri et al., 2018): “Warming trend/ Extreme temperature/ Drying Trend” as 29.93%; “Extreme precipitation” as 30.17%; “Snow cover” as 19.70%; “Damaging cyclone” as 20.20%; and “Sea-level rise” as 30.17% respectively. Therefore, we can get a Climate risk index for each seaport at the highest level.

The weights of “Climate threats” for airports come from the same sensitivity study for different airports (Forzieri et al., 2018): “Warming trend/ Extreme temperature/ Drying Trend” as 29.78%; “Extreme precipitation” as 19.11%; “Snow cover” as 25.6%; “Damaging cyclone” as 25.56%; and “Sea-level rise” as 19.11% respectively. Therefore, we can get a climate risk index for each airport at the highest level.

3.4.5. Step 5: Synthesising all evaluations by the Evidential reasoning algorithm

By implying ER equations mentioned in Section 3.3, the Climate risk index of each investigated seaports and airports can be evaluated from the lowest level to the top level. Calculation software Intelligent Decision System (IDS) is used for facilitating the calculation as shown in Figure 3.2. The assessment grades are given their corresponding values using a linear function as the set of {0, 0.25, 0.5, 0.75, 1} for {“Low risk”, “Moderately low risk”, “Medium risk”, “Moderately high risk”, “High risk”}. IDS uses the concept of a utility interval to characterise the unassigned degree of belief (unknown percentage). The ER algorithm produces a utility interval which is enclosed by the two extreme cases where the unassigned belief moves either to “Slightly preferred with a minimum utility value” or to “Greatly preferred with a maximum utility value”.

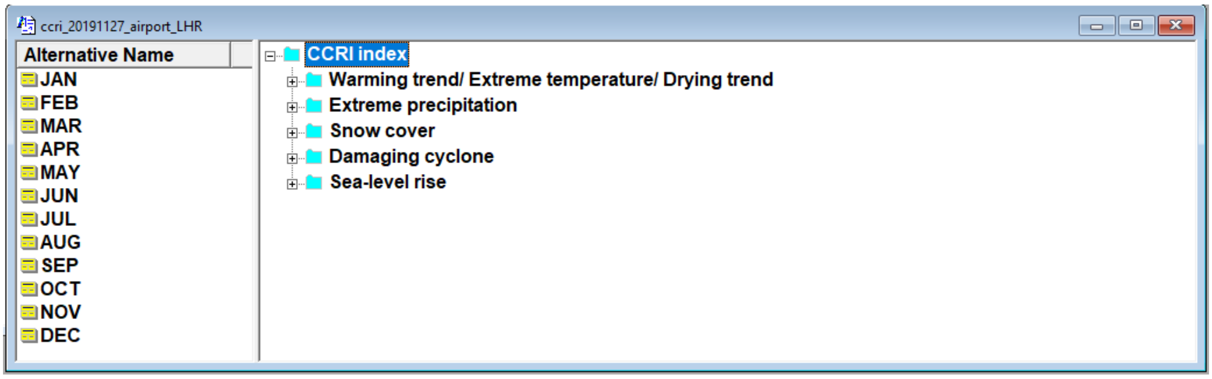

Figure 3.2 Screen capture of Intelligent Decision System

3.5. Demonstration by selected seaports and airports

By assessing climate risk index of twelve selected seaports and eleven selected airports by the formulations from Section 3.3, comparisons are conducted between locations and months. Met office defines winter as December to February, and summer as June to August. Therefore, the climate datasets of January and July have been chosen to represent winter and summer. Also, now and future, as known as historical data and forecasting data, are compared for observing the climate change impacts for measuring climate vulnerability changes from now to 2050.

3.5.1. Comparison between locations and seasons for seaports

By obtaining the Climate risk index of the twelve seaports in January in Figure 3.3 and July in Figure 3.4, Climate risk indexes of the twelve seaports in both summer and winter are shown. In Table 3.17, a Climate risk index comparison between different locations and different seasons takes place. Ranks are given to seaports by comparing their Climate risk indexes in the same month. The average value is taken for comparison if the result is incomplete.

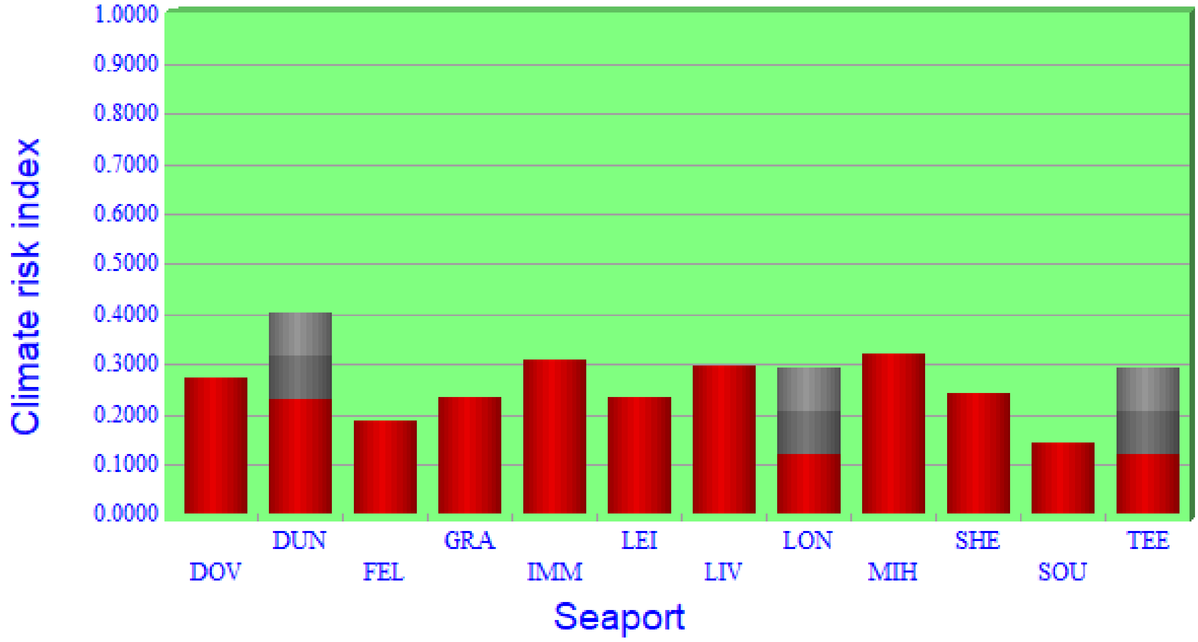

Figure 3.3 Climate risk indexes of twelve seaports in January

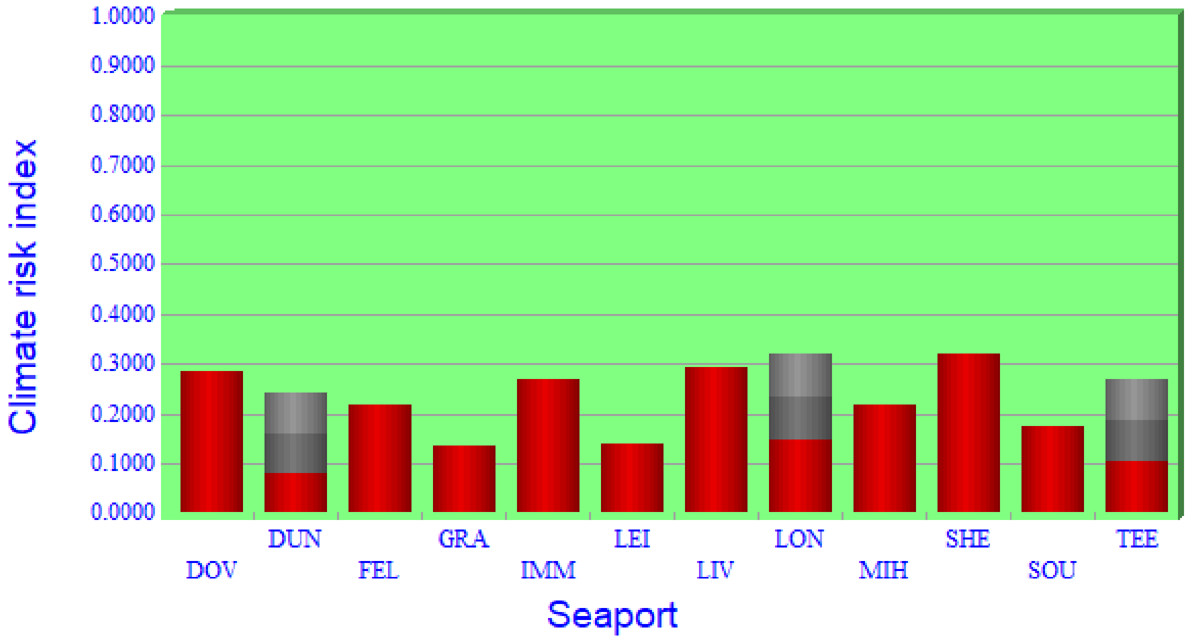

Figure 3.4 Climate risk indexes of twelve seaports in July

By obtaining the Climate risk indexes of six seaports of January and July in Figure 3.3 and 3.4, the risk difference between seasons can be observed in Table 3.17. There are two main findings. First, some northern seaports, including Dundee and Grangemouth, obtain a higher value in January and a lower value in July, and vice versa. Felixstowe and Southampton in the south are riskier in summer, and safer in winter. For the ports in the middle of the UK such as

Liverpool and Hull, they rank nearly the same in winter and summer, and they have a higher index in winter.

Table 3.17 Climate risk indexes of twelve seaports in January and July

Location	**DOV**	**DUN**	**FEL**	**GRA**	**IMM**	**LEI**
January	0.2726	0.3169	0.1878	0.2323	0.3083	0.2355
Rank	5	2	11	8	3	7
July	0.2988	0.2049	0.3225	0.2420	0.1437	0.2066
Rank	3	10	7	12	4	11
	LIV	**LON**	**MIH**	**SHE**	**SOU**	**TEE**
January	0.2988	0.2049	0.3225	0.2420	0.1437	0.2066
Rank	4	10	1	6	12	9
July	0.2930	0.2339	0.2197	0.3210	0.1768	0.1888
Rank	2	5	6	1	9	8

3.5.2. Comparison between months for seaports

By the comparison between different months, we can spot the dangerous seasons. FEL and GRA are chosen places for a demonstration in Figures 3.5 and 3.6 and Table 3.18. The highest indexes of the two ports are both existing in July, and FEL sustains the highest value in August. The lowest Climate risk indexes of the two ports take place in November and September respectively. 0.1384 is the minimum Climate risk index of FEL throughout the twelve months, and that of GRA is 0.1054. By comparing indexes between the highest and lowest indexes, FEL scores 23.48% higher than the lowest index in January, and that in July is 37.53%. Then, GRA scores 38.14% higher than the lowest index in January, and it is the lowest in July. Therefore, the seasonal climate differences of two ports are at different scales. It is possible for further cooperation for climate resilience. For example, as FEL is facing a higher rise in climate risks in summer while GRA is facing riskier in winter, relief operations or seaport network service can be planned between two seaports as they have different monthly climate risk patterns.

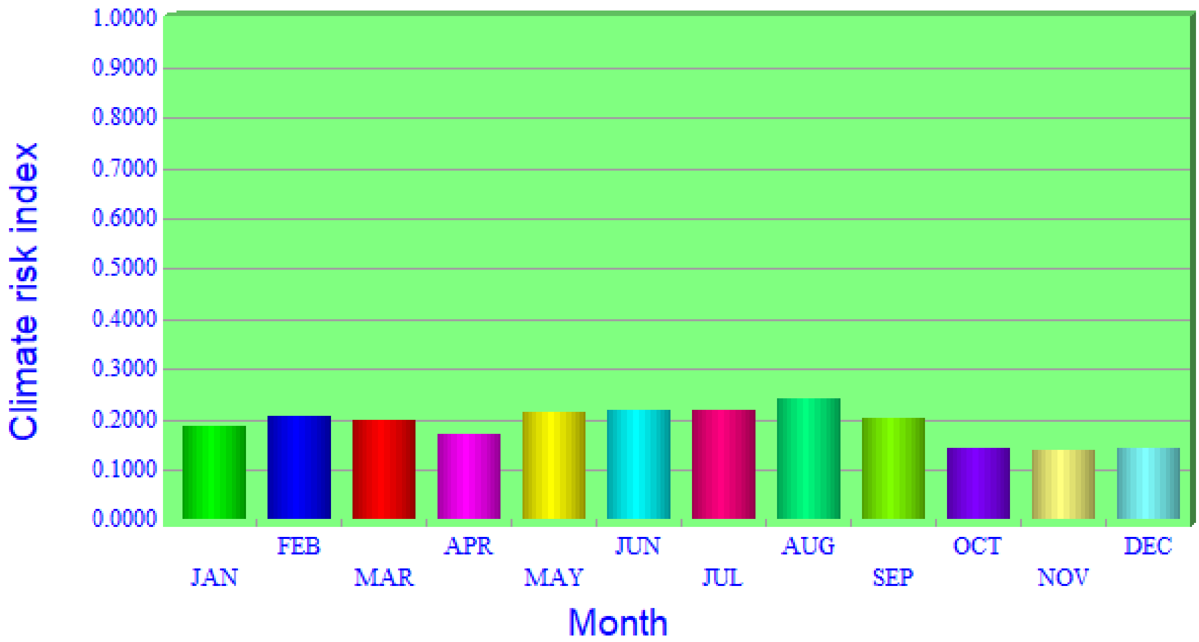

Figure 3.5 Monthly climate risk indexes of Felixstowe port

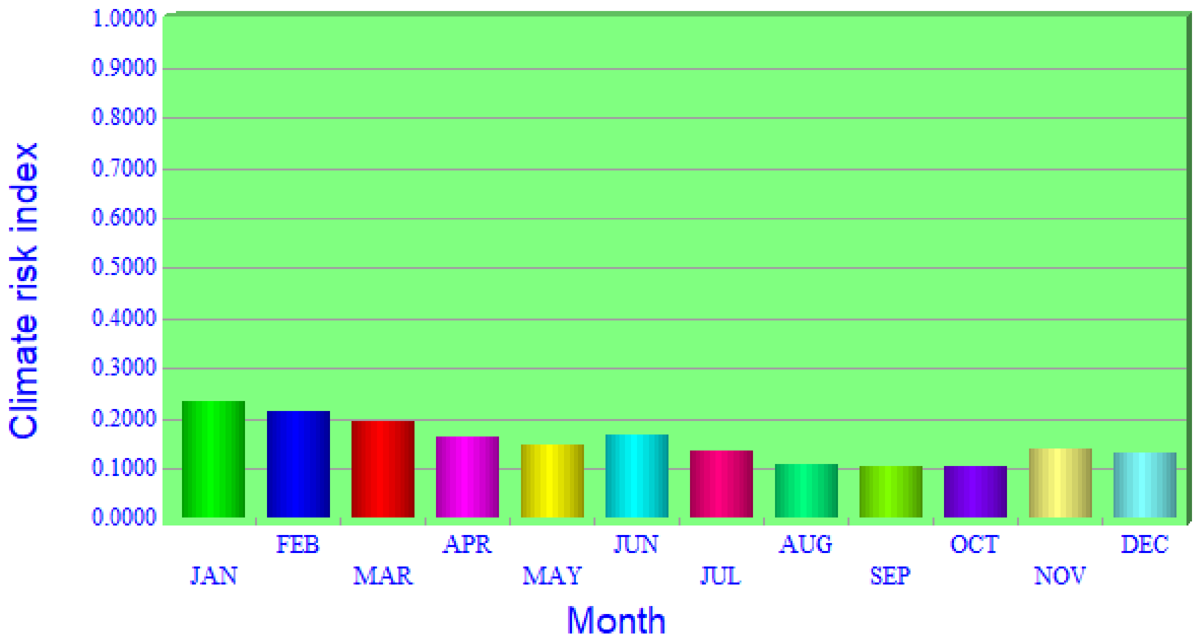

Figure 3.6 Monthly climate risk indexes of Grangemouth port

Table 3.18 Climate risk indexes of Felixstowe port and Grangemouth port in all months

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
FEL	0.1878	0.2059	0.2	0.1723	0.215	0.2182
Rank	8	5	7	9	4	3
GRA	0.2333	0.2151	0.193	0.1629	0.1487	0.1673
Rank	1	2	3	5	6	4
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
FEL	0.2186	0.2409	0.202	0.1456	0.1384	0.145
Rank	2	1	6	10	12	11

GRA	0.137	0.1075	0.1054	0.106	0.1384	0.1302
Rank	8	10	12	11	7	9

3.5.3. Comparison between now and future for seaports

The final analysis is to compare the now and future data. Figures 3.7 and 3.8 are used to observe the changes of Climate risk indexes of January and July in twelve seaports. Then, a comprehensive comparison takes places for FEL and GRA in Table 3.15. Futures average scores are used to compare to those of now. Then, the January dataset increases by 23.07%, that of July increases by 95.61%.

For the two chosen seaports, the Climate risk indexes from two locations increase more significantly in January, and they are increased by 49.68% and 43.82% respectively. In January, GRA increases more significantly by 126.50%, and that of FEL increases by 89.38% only. By the comparison between now and the future, the trend of climate vulnerability changes can be visualised. Also, the changes in climate risk indexes are differences between locations and months. Therefore, concerning such changes and findings, such analysis is necessary to be done for different seaports to understand the climate risk changes in the future.

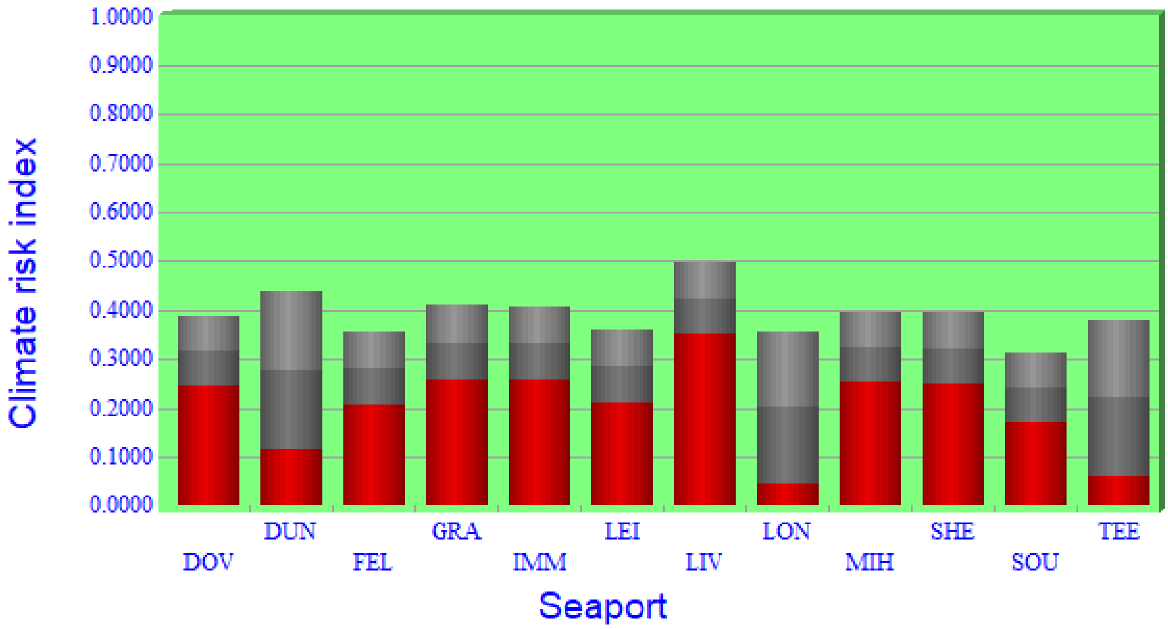

Figure 3.7 Future climate risk indexes of twelve seaports in January

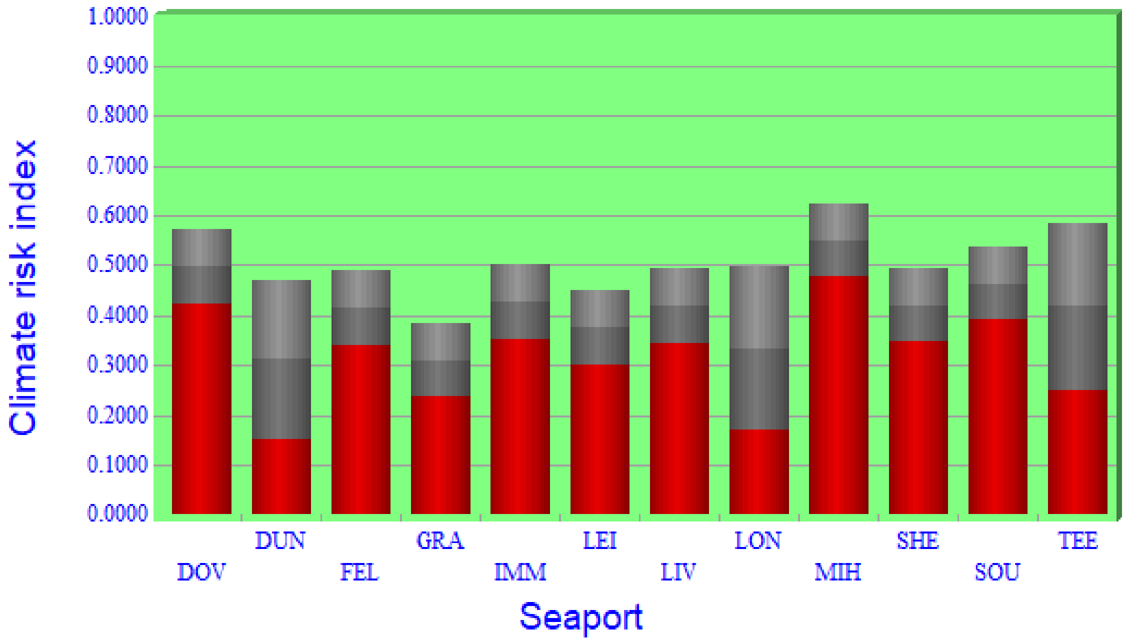

Figure 3.8 Future climate risk indexes of twelve seaports in July

Table 3.19 Future Climate risk indexes of Felixstowe port and Grangemouth port

Seaport	**FEL**		**GRA**	
Month	**January**	**July**	**January**	**July**
Now	0.1878	0.2193	0.2323	0.1370
Best Possible Future	0.2078 (+10.65%)	0.3403 (+55.18%)	0.2586 (+11.32%)	0.2375 (+73.36%)
Average Future	0.2811 (+49.68%)	0.4153 (+89.38%)	0.3341 (+43.82%)	0.3103 (+126.50%)
Worst Possible Future	0.3544 (+88.71%)	0.4903 (+123.58%)	0.4096 (+76.32%)	0.3831 (+179.64%)

3.5.4. Comparison between locations and seasons for airports

By obtaining the Climate risk indexes of the twelve seaports in January in Figure 3.9 and July in Figure 3.10, Climate risk indexes of the eleven airports in both summer and winter are shown. In Table 3.20, a Climate risk indexes comparison between different locations and different seasons takes place. Ranks are given to airports by comparing their Climate risk indexes in the same month.

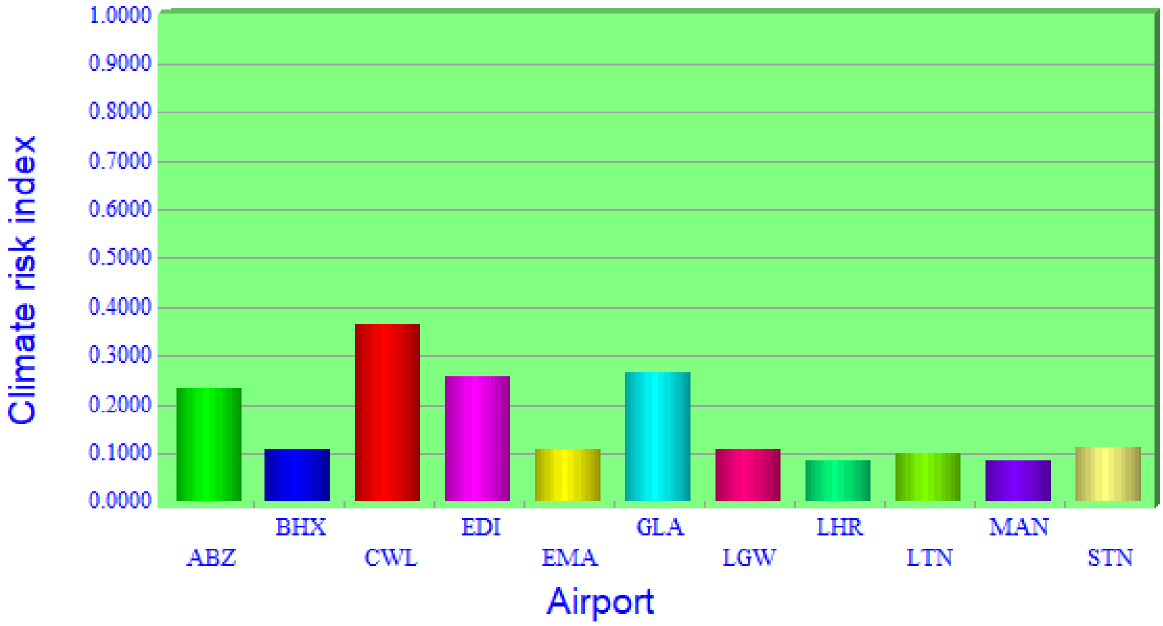

Figure 3.9 Climate risk indexes of eleven airports in January

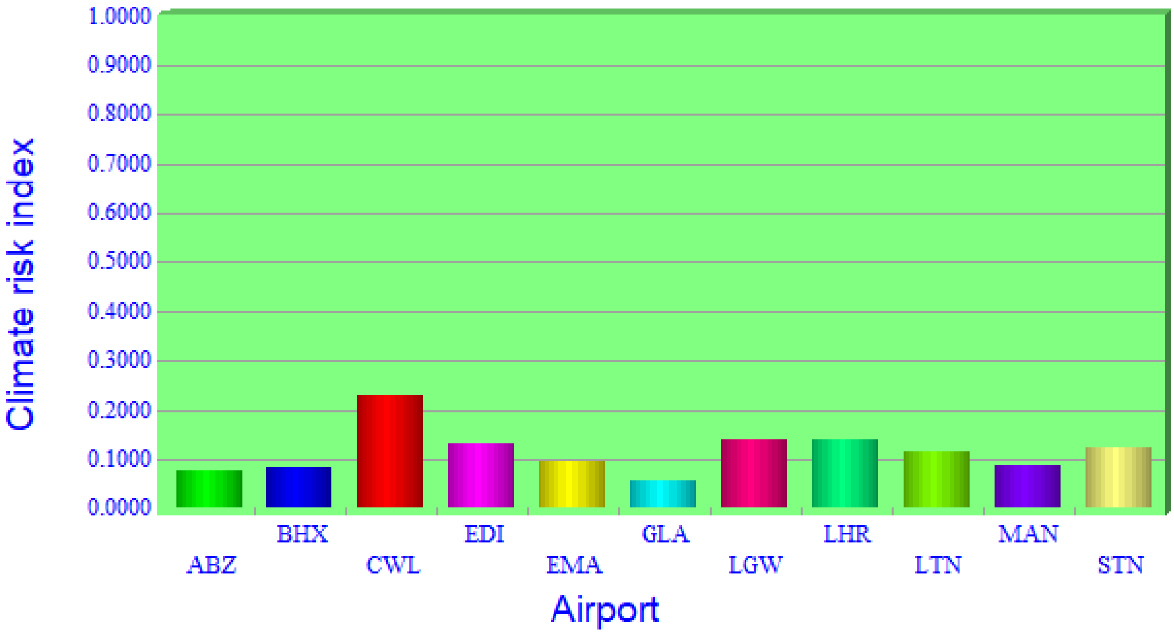

Figure 3.10 Climate risk indexes of eleven airports in July

Table 3.20 Climate risk indexes of eleven airports in January and July

Location	**ABZ**	**BHX**	**CWL**	**EDI**	**EMA**	**GLA**
January	0.2357	0.1089	0.3649	0.2595	0.107	0.267
Rank	4	7	1	3	8	2
July	0.0784	0.0851	0.2313	0.1317	0.0974	0.0559
Rank	10	9	1	4	7	11
	LGW	**LHR**	**LTN**	**MAN**	**STN**	
January	0.1092	0.084	0.1004	0.0849	0.1138	
Rank	6	11	9	10	5	
July	0.1396	0.1406	0.1163	0.0876	0.1253	

Rank	3	2	6	8	5

By observing the results of January and July, we can see the trend of CCRI scores changes. CWL is with the highest risk in both January and July because of the risk from sea-level rise. Besides CWL, we can observe the score differences between the northern part and the southern part of the United Kingdom. LHR, LGW and LTN have higher scores and ranks in July compared to those in January. ABZ, EDI and GLA have a different nature compared to the other airports. The airports in the middle of the UK, such as BHX and MAN, have relatively low CCRI scores and fewer differences between winter and summer.

3.5.5. Comparison between months for airports

By comparing Climate risk indexes between different months, we can find the climate risk levels in different seasons. EDI and LHR are the chosen places for study in Figure 3.11 and 3.12. For EDI, it is with a higher Climate risk index from December to March and relatively low during the summer. The highest index takes place in December and the lowest index takes place in October. For LHR, it is with a higher Climate risk index from July to August and relatively low during the summer. The nature is opposite to that of EDI. In Table 3.21, the higher index takes place in July and the lowest index takes place in November. Besides, the lowest monthly Climate risk index of EDI is higher than the highest monthly Climate risk index of LHR. It comes with this big difference because EDI is by the coast.

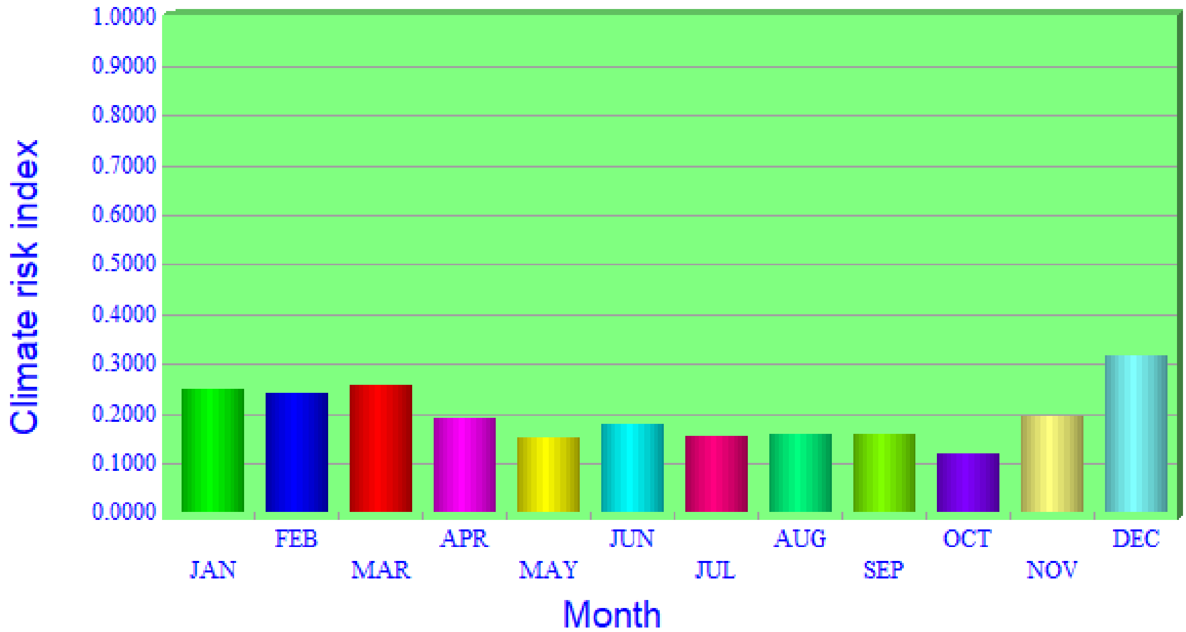

Figure 3.11 Monthly climate risk indexes of Edinburgh airport

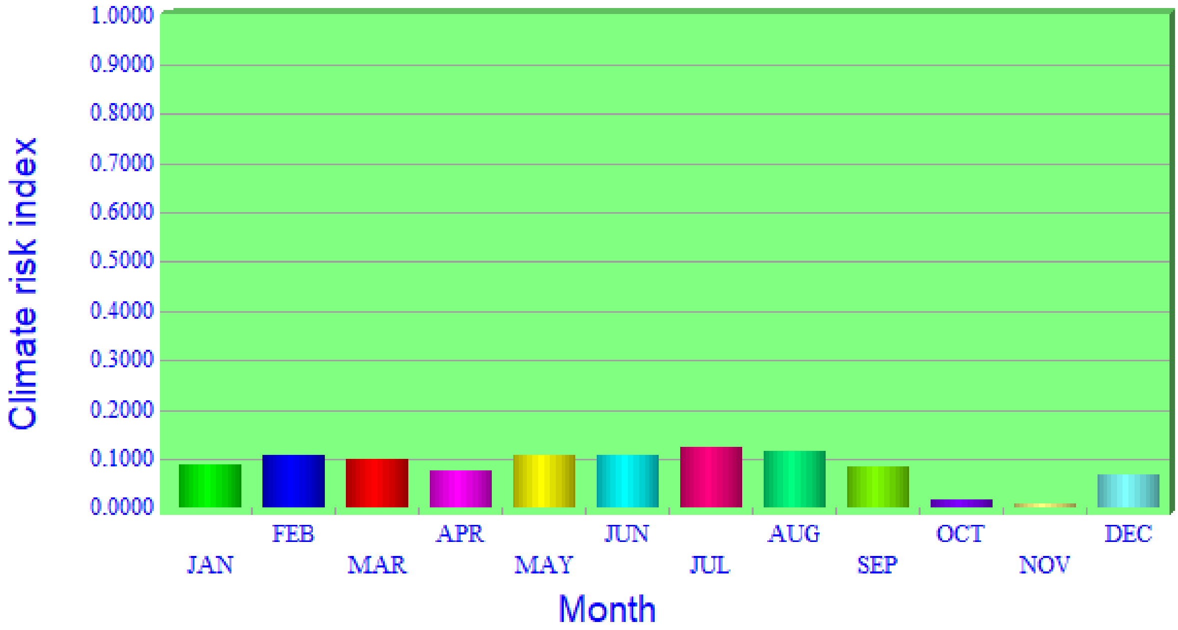

Figure 3.12 Monthly climate risk indexes of Heathrow airport

Table 3.21 Monthly Climate risk indexes of Edinburgh airport and Heathrow airport

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
EDI	0.2514	0.2428	0.2567	0.1901	0.1526	0.1798
Rank	3	4	2	6	11	7
LHR	0.0889	0.1084	0.1024	0.0762	0.1066	0.108
Rank	7	3	6	9	5	4
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
EDI	0.1549	0.1613	0.1599	0.121	0.1935	0.315
Rank	10	8	9	12	5	1
LHR	0.1228	0.1146	0.0849	0.0184	0.0106	0.0641
Rank	1	2	8	11	12	10

3.5.6. Comparison between now and future for airports

The final analysis is to compare the now and future data. Figures 3.13 and 3.14 are used to observe the changes of Climate risk indexes of January and July in eleven airports. CWL still gets the highest Climate risk index in both seasons in the future. Average future Climate risk indexes averagely increase by 17.42% and 142.30% in January and July, respectively. The further comparison between EDI and LHR is shown in Table 3.22. Comparing average future Climate risk indexes to those of now, the Climate risk indexes from two locations increase more significantly in July, and they are increased by 110.33% and 102.13% respectively. In January, EDI increases by 17.42%, and that of LHR decreases by 15.48% only. By the comparison between now and future, the trend of climate vulnerability changes can be visualised. Also, the changes in Climate risk indexes are differences between locations and months. Therefore, concerning such changes and findings, climate adaptation resources can be allocated in a more effective way, especially at coastal airports.

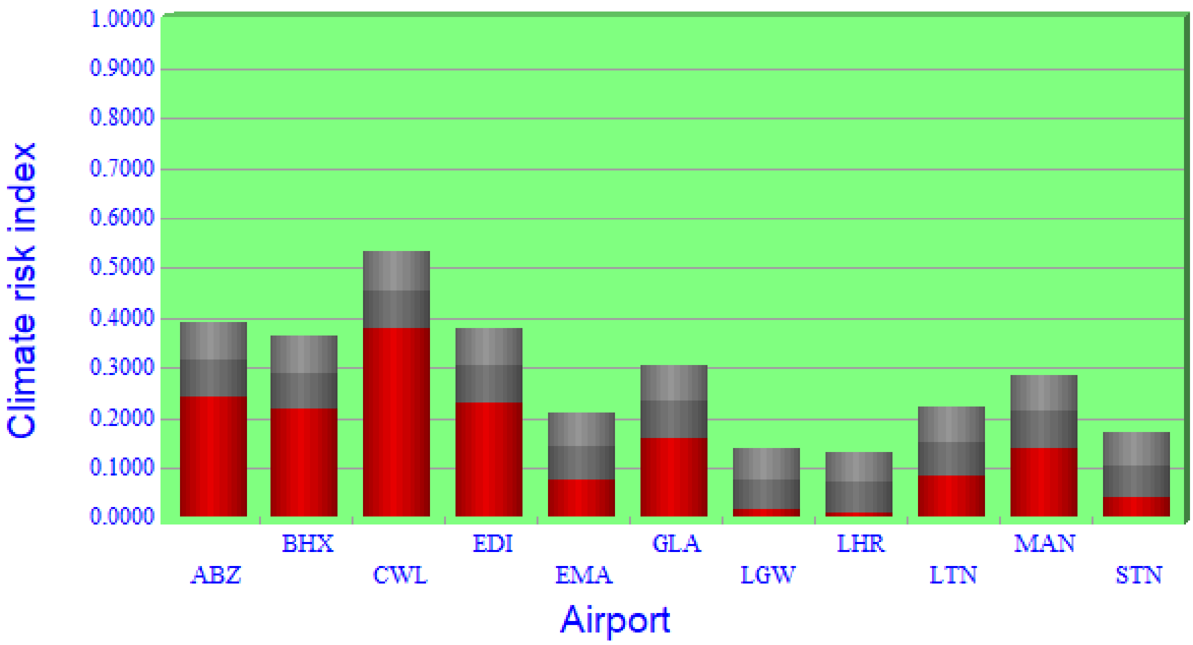

Figure 3.13 Future climate risk indexes of eleven airports in January

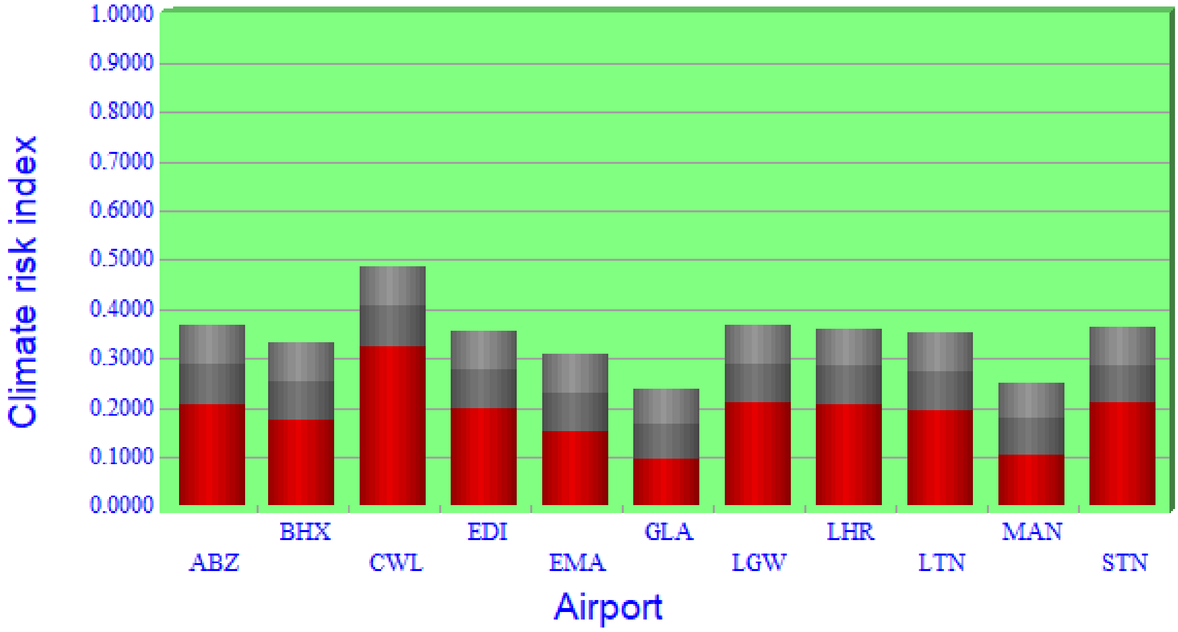

Figure 3.14 Future climate risk indexes of eleven airports in July

Table 3.22 Future Climate risk indexes of Edinburgh airport and Heathrow airport

Airport	**EDI**		**LHR**	
Month	**January**	**July**	**January**	**July**
Now	0.2595	0.1317	0.0840	0.1406
Best Possible Future	0.2307 (-11.10%)	0.1986 (+50.80%)	0.0107 (-87.26%)	0.2064 (+46.80%)

Average Future	0.3047 (+17.42%)	0.2770 (+110.33%)	0.0710 (-15.48%)	0.2842 (+102.13%)
Worst Possible Future	0.3787 (+45.93%)	0.3554 (+169.86%)	0.1313 (+56.31%)	0.3620 (+157.47%)

3.6. Comparative analysis on seaports and airports by Climate change risk indicator framework

The comparative analysis on the CCRI framework takes place by comparing the Climate risk indexes of a seaport and an airport in the same region. In Table 3.23, a table for comparing FEL and LHR, a seaport and an airport in the south, is shown. For the existing situation, LHR has a higher risk in January than July and FEL vice versa. Then, they will experience a higher risk increase in July compared to January. In the future, LHR will experience a more significant boost in climate risks in July compared to FEL, and FEL will experience a more significant boost in climate risks in January compared to LHR.

Table 3.23 Future climate risk indexes of Felixstowe port and Heathrow airport

Seaport/Airport	**FEL**		**LHR**	
Month	**January**	**July**	**January**	**July**
Now	0.1878	0.2193	0.0840	0.1406
Best Possible Future	0.2078 (+10.65%)	0.3403 (+55.18%)	0.0107 (-87.26%)	0.2064 (+46.80%)
Average Future	0.2811 (+49.68%)	0.4153 (+89.38%)	0.0710 (-15.48%)	0.2842 (+102.13%)
Worst Possible Future	0.3544 (+88.71%)	0.4903 (+123.58%)	0.1313 (+56.31%)	0.3620 (+157.47%)

In Table 3.24, a table for comparing EDI and GRA, a seaport and an airport in the north, is shown. For the existing situation, EDI and GRA have a higher risk in July than January. Then, they will also experience a higher risk increase in July compared to January. Compared to the infrastructures in the south, the average future CCRI index differences between January and July are smaller. In other words, FEL and LHR should be more alerted on climate change in summer, and EDI and GRA should be more alerted on climate change in winter. Furthermore, the average increases of CCRI indexes in January and July on seaports are 23.07% and 95.61% respectively, and those on the airport are 44.83% and 142.30%. Therefore, airports in the UK should be cautioned on climate change adaptation compared to seaports in the UK.

Table 3.24 Future climate risk indexes of Edinburgh airport and Grangemouth port

Airport/Seaport	**EDI**	**GRA**

Month	January	July	January	July
Now	0.2595	0.1317	0.2323	0.1370
Best Possible Future	0.2307 (-11.10%)	0.1986 (+50.80%)	0.2586 (+11.32%)	0.2375 (+73.36%)
Average Future	0.3047 (+17.42%)	0.2770 (+110.33%)	0.3341 (+43.82%)	0.3103 (+126.50%)
Worst Possible Future	0.3787 (+45.93%)	0.3554 (+169.86%)	0.4096 (+76.32%)	0.3831 (+179.64%)

3.7. Discussion

A new CCRI framework has been proposed and implemented to seaports and airports, and the framework is successfully used for tracking the climate risks changes monthly by the integration of a national climate dataset. Climate risks are dynamic throughout the whole year. This work package can be implemented in other regions. Then, it is possible to compare the indexes with different locations and the forecasting datasets. Therefore, the seaport alliance can use climate risk indexes for implementing climate disaster management. Furthermore, various climate threats on different seaports can be assessed, and so adaptation measures on a specific threat can be adequately implemented.

By assessing the climate risk indexes with CCRI framework, some similarities and differences can be found. By gathering the data for different climate threats, the overall climate risks can be assessed by climate risk indexes. They both have higher climate risks in summer and winter, which can be implied as the similar monthly climate risk index patterns. Also, the index variations between north and south are similar. The differences of them are airport can foresee a less climate risk increase in winter. By the study from Forzieri et al. and the climate change adaptation reports on seaports and airports, the result of comparative analysis is valid as airports suffer higher impacts from snow cover, but less impacts from sea-level rise and extreme precipitation. Airport authorities should focus more on adaptation measures on summer while seaport authorities should focus on measures in summer and winter equivalently.

The study can provide different seaport and airport stakeholders with new insights into climate vulnerabilities assessment and climate change adaptation. There are three directions for further developments. First, some climate events, such as fog and seasonal variation of wind, are without small area climate data to support them. Thus, interviews on seaport stakeholders can be done, and the qualitative information can be implemented into the CCRI framework by FER. Second, adaptive capacity, sensitivity, and social-economic factors in a regional and national scale can be collected to enhance the CCRI framework development. Lastly, the CCRI framework can be applied to other kinds of transportation infrastructure, such as airports and railway stations. By then, the CCRI framework can be used to develop a decision-making model for deciding suitable adaptation measures for a dedicated region with different transportation modes.

Chapter 4 An advanced Climate resilience indicator framework for seaports and airports

4.1. Summary

After constructing a CCRI framework, climate exposure is assessed by the monthly climate data. However, the framework is not enough to explore the climate vulnerability and resilience of seaports. Therefore, it is necessary to expand the framework to a broader scope and including the sensitivity and adaptive measures. By constructing this framework, it can assess the climate resilience for the whole city region. Also, an advanced CRI framework needs to weight the categories. Therefore, a nationwide questionnaire is required to collect ideas from professionals and operators. Then, analytic hierarchy process (AHP) (Chen, 2006) is used to determine the criteria weights indirectly based on scores of relative importance for the more comprehensive framework, CRI framework, which includes exposure, sensitivity, and adaptive capacity as categories.

This chapter first provides a critical review of climate regional vulnerability assessment, open regional and logistic data in the UK in Section 4.2. Also, the selection of MCDM for weighting assignment and the open data input are reviewed in the same section. Second, the CRI assessment by the FER approach is explained step by step in Section 4.3. Third, seaports and airports in the UK are strategically selected to demonstrate the feasibility of the CCRI framework in Section 4.4, followed by the research implications and conclusion in Section 4.5.

4.2. Review for Climate resilience indicators

The literature review consists of three types of documents, regional climate vulnerability assessment, open regional and logistic data in the UK.

4.2.1. Review of regional climate vulnerability assessment

There are two different types of climate vulnerability impact assessment for seaports: seaport assessment and coastal region studies. The coastal region studies are expanding the vulnerability assessment to a city or a district scale. A review of climate vulnerability assessment on seaports is shown in Section 3.2.1, and the regional coastal climate vulnerability assessment is shown below.

A summary of the coastal region studies has been shown in Table 4.1. The coastal region studies are expanding the vulnerability assessment to a city or a district scale. Therefore, except for assessing climate threats and coastal vulnerabilities like the seaport studies, further assessments have been done. For instance, “Landslide”, “Flooding”, “Hurricane”, “Tolerance”, and “Social-economy” are the categories of specific indicators in the coastal regions studies. “Climate exposure” is defined as the group of climate stressors. “Coastal vulnerability” considers the vulnerabilities in some coastal details. Wave exposure, Coastal erosion and characteristics of coasts are included. “Landslide” and “Flooding” are the corresponding indicators for assessing the risks of specific extreme events. “Tolerance” is the group of indicators for assessing the relieving abilities of coastal areas. “Social-economy” means the social and economic characteristics of the regions nearby. Land use, transportation network and population are all included in these categories to measure the sensitivity and importance of the port cities. Before 2008, the studies are not comprehensive, and they are mainly focusing on climate threats. From 2008, more multi-criteria assessments have been done in different parts of the world. Furthermore, Pascal Briguglio (2010) and Hanson et al. (2011) have set up adaptation index, vulnerability index, and ranks for assessing the flooding risk to global coastal cities in 2010 and 2011 respectively. In 2019, McIntosh et al. evaluate seaport vulnerability by open-data indicators, and then they set up a comparative assessment of seaport for North Atlantic medium and high-use seaports. This study provides a solid platform to implement a CRI assessment for the UK seaports.

Table 4.1 Summary of climate vulnerability impact assessment for coastal regions

Location	**Multi/ Single**	**Climate exposure**	**Coastal vulner-ability**	**Land-slide**	**Flooding**	**Tolerance**	**Social-economy**	**Reference**
Australia	Multi	v			v			(Graeme and Kathleen, 1999)
Port Said Governorate, Egypt	Multi	v					v	(El-Raey et al., 1999)
Viti Levu, Fiji Islands	Single		v					(Gravelle and Mimura, 2008)
Andaman Islands	Multi	v						(Kumar et al., 2008)
Germany	Multi	v						(Sterr, 2008)
Worldwide selected cities	Multi	v	v			v	v	(Briguglio, 2010)
Worldwide selected cities	Multi						v	(Hanson et al., 2011)
Copenhagen, Denmark	Single	v	v				v	(Hallegatte et al., 2011)
Chennai, India	Multi		v		v			(Arun Kumar and Kunte, 2012)

Shanghai, China	Single		v					(Yin et al., 2013)
South Africa	Multi	v	v			v	v	(Musekiwa et al., 2015)
Southeast Florida, the U.S.	Multi	v	v			v	v	(Genovese and Green, 2015)
Port Harcourt Metropolis, Nigeria	Single				v	v	v	(Akukwe and Ogbodo, 2015)
Cayman Islands	Single	v	v					(Taramelli et al., 2015)
Sao Paulo, Brazil	Single	v	v	v	v		v	(Vitor Baccarin et al., 2016)
Greater Tokyo area, Japan	Multi	v			v	v	v	(Hoshino et al., 2016)
Kuwait	Multi		v	v	v	v	v	(Alsahli and Alhasem, 2016)
Gulf of Bejaia, Algeria	Multi	v	v	v	v		v	(Djouder and Boutiba, 2017)
Port Said Governorate, Egypt	Single		v				v	(Abou Samra, 2017)
Barcelona	Single	v	v				v	(Cortès et al., 2018)
Jamaica and Saint Lucia	Multi	v			v			(Monioudi et al., 2018)
North Atlantic region, the U.S.	Multi	v	v		v	v	v	(McIntosh and Becker, 2019, McIntosh et al., 2018)

4.2.2. Review of defining climate exposure, sensitivity, and adaptive capacity

For this study, vulnerability to climate and extreme weather is defined according to the IPCC definition of vulnerability quoted above, and the components of vulnerability are defined as follows:

- Exposure is the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC, 2014b)
- Sensitivity: The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli (McCarthy et al., 2001).

- Adaptive Capacity: Adaptive capacity is the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and resources and technologies (Parry et al., 2007).

From the summary of coastal vulnerability indices (CVI) assessment for coastal regions, three categories can be identified. Landslide, flooding, and the social economy can represent some parts of sensitivity. Then, tolerance is a measurement of adaptive capacity. Vulnerability and resilience are two theoretical concepts, sometimes defined harmoniously, and other times described oppositely (Gallopín, 2006, Tyler and Moench, 2012). In this study, they are set oppositely, the higher the vulnerability, the lower the resilience and vice versa. The framework is named as CRI framework because the ultimate findings can be used to compare vulnerabilities of different seaports, and then reference the resource allocation and strategic grouping. Füssel suggests seven factors as the minimum framework for structuring information that may guide the prioritization of international adaptation assistance which can be used as a reference for choosing CRIs in the coming section (Füssel, 2010):

- The magnitude of regional climate change
- Biophysical sensitivity
- Socio-economic exposure/ importance
- Lack of adaptive/coping capacity (non-governance)
- Lack of adaptive/coping capacity (governance)
- Environmental-economic adaptability
- Aid effectiveness (governance)

4.2.3. Review of open regional and logistic data in the United Kingdom

A comprehensive CRI framework requires data on a larger scale including exposure, sensitivity, and adaptive capacity. CRI hierarchy is based on the study by Climate change risk indicator (CCRI) framework (Poo et al., 2018a, Poo et al., 2019) and the coastal vulnerability indices (CVI) evaluation (McIntosh and Becker, 2019, McIntosh et al., 2018). Poo et al. provide an EWE based hierarchy on climate exposure, and McIntosh et al. provide a hierarchy with three categories, exposure, sensitivity, and adaptive capacity as shown in Figure 4.1

Figure 4.1 Climate resilience indicator framework

The CRI hierarchy is initially designed for comparative analysis for both seaports and airports, and this hierarchy allows the comparison between them on the same platform. Then, forty-six for seaports and forty indicators for airports have been chosen by reviewing the references and professional consultations. Some indicators are missing due to the data availability, and evidential reasoning has been used to classify incomplete data. The data are collected from the Met Office (Met Office, 2018), Climate Projection (UK Climate Projection, 2018), British Oceanographic Data Centre (BODC) (British Oceanographic Data Centre, 2018), Joint Nature Conservation Committee (JNCC) (JNCC, 2018), DEFRA (Vitolo et al., 2016), National Housing Federation (NHF) (National Housing Federation, 2019), Eurostat (eurostat, 2019), Office for National Statistics (ONS) (Fenton, 2019), Department of Transport (DfT) (Department for Transport, 2020), Climate Just (Lindley et al., 2011), Her Majesty's Land Registry (HM Land Registry) (HM Land Registry, 2020), Tom Tom International (TomTom N.V., 2017), and UK Environment Agency (EA) (Envirnment Agency, 2020). For seaports only, some data are collected from World Port Index (Agency, 2014), Maritime UK (Maritime

UK, 2019), and UK Ports (UK Ports). For airports only, some data are found from Civil Aviation Authority (CAA) (CAA, 2020), HM Government (HM Government, 2017) and airport codes (Fubra Limited, 2020). They are all open data available from the associated websites. The frameworks for seaport and airport are shown in Annex 2 and Annex 3, respectively.

The following three associations provide data for environmental sensitivity The Joint Nature Conservation Committee (JNCC) is the public body that is responsible to UK-wide and international nature conservation which is suitable to provide data for surrounding environment, such as the number of Special Areas of Conservation in seaport county. UK Air Information Resources (UK AIR) is provided by DEFRA on daily air pollution record count of days with Air Quality Daily index higher than moderate can be counted. National housing federation (NHF) is a trade association representing housing providers in England, and it can provide brownfield ratio for assessing the sensitivity of hazardous materials (HAZMAT).

For Built asset sensitivity, land-side and water-side assets are needed to be considered, including shelter, entrance restrictions, overhead limitations, water depth and tidal range. The data is all found from World Port Index, which is published by National Geospatial-Intelligence Agency. It provides a tabular listing of thousands of seaports throughout the world, describing their locations, characteristics, known facilities, and available services, and some of them are chosen for analysis in this advanced CRI framework.

For Economic sensitivity, regional , seaport, and airport indicators are collected, and the data are from Eurostat, ONS, Maritime UK, and UK Department of Transport. Eurostat is a Directorate-General of the European Commission for providing statistics information for European cities, and ONS is the executive office of the UK Statistics Authority. Maritime UK is an organisation for promoting UK maritime sector, and DfT is the government department in charge of English transport network and some transport issues in Scotland, Wales, and Northern Ireland. Eurostat provides Gross domestic product (GDP), and ONS provides Gross Value Added (GVA) per head for the region. DfT and CAA provide market share, and Maritime UK and HM office provide direct employment for seaports and airports.

For social sensitivity, Climate Just and HM Land Registry are the two organisations to provide open dataset. Climate Just is an information tool designed by Environmental agency to help on delivering equitable responses to climate change at different local authorities, and it provides socio-spatial vulnerability indices for surrounding population's sensitivity. HM Land Registry is a non-ministerial department of the Government of the United Kingdom, and it provides the details of UK house price.

For operational efficiency, TomTom International is a Dutch multi-national developer and creator of location technologies, such as congestion index for the advanced CRI framework. Also, World Port Index and Airport code provide the detail of direct rail connections.

For water-capacity, the details of harbour size are collected from World Port Index, and the details of passengers and freights are collected from DfT.

For Land-side flexibility, UK Ports is the organisation providing an extensive guide to the UK's seaports, and it give details on berths. Then, the details of crane and lift are gathered from World Port Index. Then, Environment Agency is a non-departmental public body to provide the availabilities on seaport planning, including master plans, adaptation plans, and sustainability plan. Finally, the annual percentage change in throughput and seaport market share are collected from DfT for assessing seaport growth. Those for airports are collected from CAA.

4.3. Climate resilience indicator assessment by the Fuzzy evidential reasoning approach

The mechanism of CRI assessment can be referred from that of the in Section 3.3. The differences between them are methods of weight assignments and the data generation of climate exposure. It is different because there are no references can be found to start up, and thus requiring weighting assignment. As the monthly extremes are commonly used for assessing the climate risks, therefore monthly records are suitable for assessment. The highest value among twelve months is chosen because climate resilience index is not designed as seasonal as the parameters, such socio-spatial vulnerability index and congestion index of climate sensitivity and adaptive capacity. For weight assignment, expert questionnaires and AHP are used for CRI framework, and the highest grading of monthly climate exposure data is chosen for assessment. CRI assessment can be divided into five steps.

4.3.1. Defining the Climate resilience indicator hierarchy

CRI hierarchy is based on the study by Climate change risk indicator (CCRI) framework (Poo et al., 2018a, Poo et al., 2019) and the coastal vulnerability indices (CVI) evaluation (McIntosh and Becker, 2019, McIntosh et al., 2018). Poo et al. provide an EWE based hierarchy on climate exposure, and McIntosh et al. provide a hierarchy with three categories, exposure, sensitivity, and adaptive capacity. Then, two frameworks are both reviewed by related professions, and they are coherent until sub-sub-category level.

For exposure, seven sub-categories are included: damaging cyclone, sea-level rise, warming trend/ extreme temperature/ drought, precipitation hazard, snow cover/ frost cover, seasonal changes in fog events, and seasonal changes in wind events. The data are collected from the Met office, Climate Projection and BODC. The sub-sub-categories of exposure are the measurements of the EWEs, such as temperature and relative humidity.

For sensitivity, it can be split into four sectors, environmental sensitivity, built asset sensitivity, economic sensitivity, and social sensitivity. Environmental sensitivity data is collected from JNCC, UK Air Information Resources, and National Housing Federation. For built asset sensitivity, airport and seaport both lack of indicators on landside, while seaport has plenty of indicators, including shelter, channel limitations, water depth, and tidal range, on waterside. For economic sensitivity, regional data is from Eurostat and ONS. Then, airport data is from HM government and CAA. For economic sensitivity, surrounding population data is from Climate Just, and surrounding structures/ asset data is from HM Land Registry.

For adaptive capacity, the congestion index is from Tom Tom International, and planning indicators are from the UK Environmental Agency. Then, there is a lack of indicators for seaport operation efficiency, and punctuality statistics are chosen from the CAA for airports. For the growth, airport data is collected from the CAA, and that of the seaport is collected from the UK Department of Transport. The remaining capacity data is collected from CAA, World Airport Code, World Port Index, UK Department of Transport, and the UK Department of Transport.

The weights of all the CRIs are generated from an AHP survey. The questionnaire was sent to professionals in seaports and airports to obtain the weights. Ten seaport responses and eleven airport responses have been collected, and the geometric mean is used to present a single value from the questionnaire findings. The questionnaire is designed on Jisc online platform and distributed by email. Consistent index (ConI) are calculated for all weight assignments required for weighting the whole CRI framework, and Random index (RI) is collected from Saaty (1990) as shown in Table 4.2. Then, Consistent ratio (ConR) can be calculated by dividing ConI by RI.

Table 4.2 Random index for different number of factors

Number of factors	2	3	4	5	6	7	8	9	10
Random index	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

ConRs of all branches on seaport framework and airport framework are calculated to validate the framework as shown in Annex 4 and Annex 5. All ConRs are lower than 0.11, which mean the framework acceptable to be used for future assessments.

4.3.2. Defining the assessment grades

For the indicators from the Met office, 5 x 5 km monthly gridded observational datasets of the whole United Kingdom are collected. Then, 60th, 70th, 80th, 90th and 95th percentile values are used to divide the upper bound (UB) assessment grades into five categories, and 40th, 30th, 20th, 10th and 5th percentile values are used to classify the lower bound (LB) assessment grades. All datasets can fit the set with five linguistic assessment grades by the utility mapping technique, which has been commonly implemented with FER (Yang et al., 2009).

As the maximum sea level records and maximum skew surge records from BODC are presented by extreme data, we separated them into five groups by five values at 10th, 30th, 50th, 70th, and 90th percentiles of records from all 45 ports data.

As the gradings of indicators from Met office and BODC are shown in Section 3.4.2, they are exempted from being shown again in this section. The other data is considered for quantitative assessment first. Otherwise, gradings are set up with the reference from the corresponding organisations in Table 4.3.

Table 4.3 Summary Climate resilience indicators for sensitivity and adaptive capacity

Description	**Organization**	**Unit**	**Type**
Number of Special Areas of Conservation in port county	JNCC	N/A	Quantitative
Count of days with Air Quality Daily index > 5	DEFRA	Days	Quantitative
Brownfield ratio higher than 0.5%	NHF	yes / no	Qualitative
Shelter Afforded	World Port Index	N/A	Qualitative
Presence or absence of entrance restrictions	World Port Index	N/A	Qualitative
Presence or absence of overhead limitations	World Port Index	N/A	Qualitative
The controlling depth of the principal or deepest channel at chart datum	World Port Index	m	Qualitative

The greatest depth at chart datum alongside the respective wharf/pier	World Port Index	m	Qualitative
Mean tide range at the port	World Port Index	m	Quantitative
Gross domestic product (GDP)	Eurostat	£million	Quantitative
Gross Value Added (GVA) per head	ONS	£	Quantitative
Seaport market share	DfT	%	Quantitative
Direct employment	Maritime UK	Number of jobs	Quantitative
Socio-spatial vulnerability index - flood	Climate Just	N/A	Quantitative
Socio-spatial vulnerability index - heat	Climate Just	N/A	Quantitative
UK House Price Index	HM Land Registry	£	Quantitative
Congestion index	TomTom N.V.	N/A	Qualitative
Presence of direct rail connections	World Port Index	N/A	Qualitative
Number of berths	UK Ports	N/A	Quantitative
Number of crane types	World Port Index	N/A	Qualitative
Number of lift types	World Port Index	N/A	Qualitative
Total passenger traffic	DfT	Passenger	Quantitative
Total freight traffic	DfT	Tonnage	Quantitative
Do Seaport/Airport Master Plans consider resilience?	EA	yes / no	Qualitative
Do State and Local Adaptations Plans consider resilience?	EA	yes / no	Qualitative
Does the seaport/airport have sustainability plan?	EA	yes / no	Qualitative
Positive annual percentage change in throughput	DfT	yes / no	Qualitative
Positive annual percentage change in seaport/airport market share	DfT	yes / no	Qualitative

The indicators are considered for quantitative assessment first. The details of twenty-three strategic locations, twelve seaports and eleven airports are compared, and a maximum value is sorted out for each indicator. For example, the maximum and minimum values are "Number of Special Areas of Conservation in the port county" is 74 and 0. The maximum region is South East, which includes MIH and CWL. The minimum regions are Suffolk, Lothian, Birmingham City, Glasgow, and they include FEL, GRA, LEI, BHX, and DEI. Otherwise, gradings are set up with the reference from the corresponding organisations, including World Port Index and Climate Just. For example, five gradings for "Shelter Afforded" are defined by World Port Index, and they are "E – Excellent", "G – Good", "F – Fair", "P– Poor", and "N– None".

4.3.3. Evaluating seaports and airports using climate data

The input dataset is used to evaluate seaports using climate data from the lowest level of the CCRI framework. Twelve seaport groups mentioned in Table 3.3, “Dover (DOV)”, “Dundee (DUN)”, “Felixstowe (FEL)”, “Grangemouth (GRA)”, “Immingham (IMM)”, “Leigh (LEI)”, “Liverpool (LIV)”, “London (LON)”, “Milford Haven (MIL)”, “Sheerness (SHE)”, “Southampton (SOU)”, and “Tees (TEE)”, are chosen for a demonstration as they are near different urban areas and they are mostly assigned by the UK government to implement an adaptation plan.

For the airport selection, ten airport reporting bodies mentioned in Table 3.7, invited for submitting climate change adaptation reports about airport risks under the Climate Change Act 2008 are chosen to be evaluated. Also, ABZ is chosen too as it is serving an urban area in the north, and it is a top ten busiest airport in the UK for both passengers and freight.

4.3.4. Evaluating seaports and airports by indicators from the lowest level to top-level criteria

Apart from CCRI framework, CRI framework has more than three layers, and the weight assignment comes from the AHP survey results. Therefore, the final climate resilience indices of seaports can be evaluated from indicators, which mean from the lowest level to the highest level.

4.3.5. Synthesizing all evaluations using the Evidential reasoning algorithm

By implying ER equations in Section 3.3, the Climate resilience index of each investigated seaport can be evaluated from the lowest level to the top level. Calculation software Intelligent Decision System (IDS) is used for facilitating the calculation. IDS uses the concept of a utility interval to characterise the unassigned degree of belief (DOB), known as an unknown percentage.

4.4. Demonstration by selected seaports and airports

In this section, seaports and airports are evaluated by different perspectives, exposure, sensitivity and adaptative capacity. The ranks are given to seaports and airports respectively, and they are arranged in order from high resilience to low resilience. Furthermore, the ranks of DOB are given to different categories and the overall index. The results for seaports and airports are shown separately in Table 4.4 and Table 4.5, respectively.

DOV is the most climate-exposed seaport, while GRA ranks the highest as they are the least climate-exposed seaport. DOV is the least climate-sensitive seaport, and MIH is the most climate-sensitive airport. LEI has the highest adaptive capacity. SOU ranks the overall highest, and MIH ranks the overall lowest.

Table 4.4 Climate resilience indexes of twelve seaports

Seaport	Exposure	Rank	Sensitivity	Rank	Adaptive capacity	Rank	Overall	Rank
DOV	0.5835	12	0.2812	1	0.2551	2	0.4265	5
DUN	0.5164	7	0.5471	10	0.3132	5	0.4567	7
FEL	0.5017	6	0.4019	6	0.5468	10	0.4909	10
GRA	0.3894	1	0.4931	9	0.4315	8	0.4205	3
IMM	0.5279	9	0.3166	4	0.5966	12	0.5053	11
LEI	0.3919	2	0.5553	11	0.07248	1	0.4641	8
LIV	0.5591	11	0.4419	8	0.3058	4	0.4486	6
LON	0.4895	5	0.3983	5	0.3718	7	0.4265	5
MIH	0.5198	8	0.6014	12	0.4838	9	0.5271	12
SHE	0.5394	10	0.2978	2	0.5476	11	0.486	9
SOU	0.4124	3	0.3055	3	0.2746	3	0.3306	1
TEE	0.4267	4	0.4167	7	0.3202	6	0.3784	2

CWL is the most climate-exposed seaport, while ABZ ranks the highest as they are the least climate-exposed seaport. STN is the least climate-sensitive seaport, and CWL is the most climate-sensitive airport. While IMM has the lowest adaptive capacity, LHR has the highest adaptive capacity. LHR ranks the overall highest, and LTN ranks the overall lowest.

Table 4.5 Climate resilience indexes of eleven seaports

Airport	Exposure	Rank	Sensitivity	Rank	Adaptive capacity	Rank	Overall	Rank
ABZ	0.3689	1	0.4514	6	0.6358	4	0.5237	4
BHX	0.4371	4	0.3589	3	0.7006	9	0.5457	7
CWL	0.5912	11	0.5684	11	0.6596	7	1.0086	11
EDI	0.4129	3	0.4746	8	0.6798	8	0.564	8
EMA	0.4519	7	0.3504	2	0.6542	6	0.5209	3
GLA	0.5201	10	0.4058	5	0.5479	2	0.5009	2
LGW	0.4605	8	0.3752	4	0.6466	5	0.5265	5
LHR	0.4424	5	0.4987	9	0.5098	1	0.4894	1
LTN	0.4465	6	0.4692	7	0.7912	10	0.6286	10
MAN	0.403	2	0.5129	10	0.6119	3	0.5397	6
STN	0.4693	9	0.3252	1	0.8078	11	0.5928	9

4.5. Comparative analysis on seaports and airports by relative weights

After demonstrating the CRI assessment on CRI framework, comparative analysis on analysis one seaports and airports is done by the weight assignment on both. A nationwide survey among the seaport and airport stakeholders in the UK is done for weighting the criteria for the CCRI framework, and the results are used in Section 4.4. Comparing weights of categories and sub-categories between seaports and airports is a by-product of the survey and it is useful to see the differences among them.

4.5.1. Top-level factors

Table 4.6 Relative weights of top-level factors between seaports and airports

Factor	Seaports	Rank	Airports	Rank
Exposure	0.4389	1	0.2622	3
Sensitivity	0.2412	3	0.3148	2
Adaptive capacity	0.3200	2	0.4230	1

Exposure is the most important category for seaports, and it is the least essential category for airports. Sensitivity is the least crucial for seaports, while adaptive capacity is the most crucial for airports.

4.5.2. Exposure factors

Table 4.7 Relative weights of exposure factors between seaports and airports

Factor	Seaports	Rank	Airports	Rank
Damaging cyclone	0.2163	1	0.1927	1
Sea-level rise	0.1635	3	0.1919	2
Warming trend/ Extreme temperature/ Drought	0.1957	2	0.1487	4
Heavy precipitation	0.1527	4	0.1767	3
Snow cover/ Frost cover	0.1057	5	0.1053	5
Fog events	0.0813	7	0.0826	7
Wind events	0.0849	6	0.1021	6

Fogs and wind events are the first and second least important sub-categories. Snow and frost cover rank the fifth on the importance. Damaging cyclone is the most essential sub-category. Warming trend affects seaports more than airports. On the other hand, they have similar levels of concern about sea-level rise and heavy precipitation.

4.5.3. Sensitivity factors

Table 4.8 Relative weights of sensitivity factors between seaports and airports

Factor	Seaports	Rank	Airports	Rank
Environmental sensitivity	0.5317	1	0.4263	1
Built asset sensitivity	0.1209	4	0.1857	3
Economic sensitivity	0.1849	2	0.1849	4
Social sensitivity	0.1626	3	0.2030	2

Environmental sensitivity is the prime sub-category within sensitivity. It occupies more than 50% on seaport sensitivity and 40% on airport sensitivity. The following rank for seaports is economic sensitivity, social sensitivity and built asset sensitivity. Moreover, that for airports is social sensitivity, built asset sensitivity and economic sensitivity.

4.5.4. Adaptive capacity factors

Table 4.9 Relative weights of adaptive capacity factors between seaports and airports

Factor	Seaports	Rank	Airports	Rank
Operational efficiency	0.4604	1	0.5306	1
Air-side capacity/ Sea-side capacity	0.2991	2	0.2417	2
Land-side capacity	0.2405	3	0.2277	3

For adaptive capacity, the importance of factors is similar. The leading factor is operational efficiency, and the following factors are Air-side capacity/ Sea-side capacity and Land-side capacity.

4.6. Comparative analysis on seaports and airports by advanced Climate resilience indicator framework

After assessing the weights of CRIs, seaports and airports are ranked and compared together. The higher rank with lower index means the infrastructure is resilient. For exposure, SOU ranks the highest and LTN ranks the lowest. ABZ ranks the highest on sensitivity, and CWL ranks the lowest. For adaptive capacity, DOV ranks the highest and MIH ranks the lowest. For the overall CRI index, LEI ranks the highest and LTN ranks the lowest. Seaports and airports are also ranked both the highest and the lowest, thus the CRI framework is statistically capable of comparing the climate resilience by the two versions of the CRI framework even though they have different missing indicators. By averaging the CRI indexes of both seaports and airports, airports have a slightly higher resilience on exposure and a slightly lower resilience on sensitivity. However, seaports have the higher adaptive capacity and general climate resilience. It means that airports should have more awareness of adaptation planning.

Table 4.10 Climate resilience indexes of seaports and airports

Seaport/ airport	Exposure	Rank	Sensitivity	Rank	Adaptive capacity	Rank	Overall	Rank
DOV	0.5835	22	0.2812	1	0.2551	2	0.4265	5
DUN	0.5164	16	0.5605	19	0.3132	5	0.4567	7
FEL	0.5017	15	0.393	9	0.5468	11	0.4909	11
GRA	0.3894	2	1.1995	23	0.4315	8	0.4205	3
HUL	0.5279	19	0.3266	5	0.5966	14	0.5053	13
LEI	0.3919	3	0.5663	20	0.07248	1	0.4641	8
LIV	0.5591	21	0.4495	13	0.3058	4	0.4486	6
LON	0.4895	14	0.4049	10	0.3718	7	0.4265	5
MIH	0.5198	17	0.6014	22	0.4838	9	0.5271	17
SHE	0.5394	20	0.296	3	0.5476	12	0.486	9
SOU	0.4124	5	0.2883	2	0.2746	3	0.3306	1
TEE	0.4267	7	0.4074	12	0.3202	6	0.3784	2
ABZ	0.3689	1	0.4514	14	0.6358	16	0.5237	15
BHX	0.4371	8	0.3589	7	0.7006	21	0.5457	19
CWL	0.5912	23	0.5684	21	0.6596	19	1.0086	23
EDI	0.4129	6	0.4746	16	0.6798	20	0.564	20
EMA	0.4519	11	0.3504	6	0.6542	18	0.5209	14
GLA	0.5201	18	0.4058	11	0.5479	13	0.5009	12
LGW	0.4605	12	0.3752	8	0.6466	17	0.5265	16
LHR	0.4424	9	0.4987	17	0.5098	10	0.4894	10
LTN	0.4465	10	0.4692	15	0.7912	22	0.6286	22
MAN	0.403	4	0.5129	18	0.6119	15	0.5397	18
STN	0.4693	13	0.3252	4	0.8078	23	0.5928	21
Seaport mean	0.4881	N/A	0.4812	N/A	0.3766	N/A	0.4468	N/A
Airport mean	0.4549	N/A	0.4355	N/A	0.6587	N/A	0.5855	N/A

Table 4.11 shows the rank of unassigned DOB. For seaports, DUN and SOU rank the highest and lowest, respectively. On the other hand, GLA rank the highest and CWL rank the lowest on the airport rank table. The maximum unassigned DOBs of seaport and airport are 0.0841 and 0.0612, respectively. Therefore, it reversely means that more than 90% of DOB is assigned for all seaports and airports.

Table 4.11 Unassigned degree of belief of twelve seaports and eleven airports

Seaport	**Unassigned DOB**	**Airport**	**Unassigned DOB**
DOV	0.037	ABZ	0.0429
DUN	0.0841	BHX	0.0494
FEL	0.0374	CWL	0.425

GRA	0.0481	EDI	0.0439
HUL	0.0371	EMA	0.0487
LEI	0.0482	GLA	0.0612
LIV	0.0369	LGW	0.0497
LON	0.0728	LHR	0.0493
MIH	0.0464	LTN	0.0486
SHE	0.0443	MAN	0.0492
SOU	0.0355	STN	0.0501
TEE	0.0725		

4.7. Discussion

By implementing FER and AHP techniques together with the collecting data, CRI assessment of the UK seaports and airport are successfully done. The finding by CRI framework is not like that of CCRI framework as the result is not strongly related to locations. Therefore, sensitivity and adaptive capacity have important roles for contributing on the final climate resilience level, which can back the national governmental bodies to resources allocation on adaptation measures.

By the comparative analysis for seaport and airport in this section, some similarities and differences can be assessed. One of the most significant similarities is that the climate resilience levels are not related to the location because of the data input for sensitivity and adaptive capacity. Also, they have the same priority on adaptive capacity factors, and similar levels of exposure and sensitivity in the CRI framework. On the other hand, there are some differences. They have different priorities on exposure and sensitivities, and different levels of adaptative capacity in the CRI framework. By the large difference between the average levels of adaptative capacity, a difference between climate resilience indexes of seaports and airports takes place.

As there are some adaptive capacity indicators specialised for one transport mode only, it cannot conclude that seaports are more adaptive capable than airports. But still, it can still show the possibilities of linking up all transportation mode by the CRI framework introduced in Section 4.2.3.

Chapter 5 Centrality assessment

5.1. Summary

This chapter aims to observe the climate vulnerabilities in different seaports and throughout the whole seaport network in the world. First, the similarities and differences between "resilience" and "vulnerability" used in the maritime supply chain are discussed. Then, a centrality assessment of port cities by a novel multi-centrality-based indicator is implemented. Afterwards, the indicators of the centrality assessment have been used to analyse together with a set of climate vulnerability and adaptation indices. These reveal that climate vulnerabilities need to be tackled within a "node" (seaport) and in the whole seaport network. By the result, twenty nodes with the highest centrality have been chosen for undergoing case study in Chapter 6.

Routing problem is chosen to be assessed to observe the influence of climate change on global shipping networks. This chapter focuses on seaport only as the routing problem is somewhat simpler for airports than seaports as the short-haul is under three hours, the medium-haul is three to six hours, long haul is six to twelve hours, and ultra-long-haul is over twelve hours. Comparing ultra-long-haul with more than thirty days for seaports, it is not necessary to implement the airline data to the routing model as the decision of flying is relatively binary.

This chapter first provides a critical review of vulnerability, resilience, centrality assessment in maritime transportation, and climate vulnerability assessment for coastal cities in Section 5.2. Second, the centrality assessment by the multi-centrality-based indicator approach is explained step by step in Section 5.3. Third, eleven airports in the UK are strategically selected to demonstrate the feasibility of the CRI framework in Section 5.4. Finally, a discussion with research implication is shown in Section 5.5.

5.2. Review for centrality assessment

5.2.1. Vulnerability and resilience

There are no commonly accepted definitions of vulnerability and resilience for climate change adaptation and maritime network. For maritime network, it can refer to the vulnerability and resilience of the transport system network. Mattsson and Jenelius have a discussion about vulnerability and resilience concepts with a transport system angle (Mattsson and Jenelius, 2015), and Joakim et al. use vulnerability and resilience concepts to advance climate change adaptation (Joakim et al., 2015). Moreover, Liu et al. analyse the different vulnerability concepts used in the maritime supply chain (Liu et al., 2018).

The first understanding of vulnerability explores the concept as the probability of a person, community or system reaching or surpassing a particular benchmark or threshold, more commonly found in the food security literature (De Leon and Carlos, 2006). The second approach defines vulnerability with exposure to hazards or threads. This definition is highlighted as the traditional risks and hazards approach identified by both Eakin and Luers (Eakin and Luers, 2006), and Füssel (Füssel, 2007). The third approach conceptualizes vulnerability as a particular condition or state of a system before a hazard, or climate-related stressor occurs, often described in terms of criteria such as susceptibility, limitations, incapacities or deficiencies, for example, the incapacity to resist the impact of a hazard or climate change (resistance) and the incapacity to cope (coping capacity) (Kelly and Adger, 2000). Then, the final approach sees vulnerability as an outcome or residual generated after any adaptation has taken place (O'brien et al., 2007).

The first approach of resilience is the “persistence of relationships within a system and is a measure of the ability of these systems to absorb the change of state variables, driving variables, and parameters, and persist” (Holling, 1973). The second concept of resilience relates more specifically to the hazards literature and is understood as the capacity to recover or “bounce back” in the aftermath of experiencing climate extremes or disasters (Paton, 2006, Ronan and Johnston, 2005). The final approach for understanding resilience is the concept related to the idea of transformation and increasing the functionality of the community after a climatic shift or extreme event. In this sense, resilience is the process of “adapting to new circumstances and learning from the disaster or climate change (Adger, 2000, Maguire and Hagan, 2007).

For maritime system vulnerability, the network vulnerability is defined as the network robustness (Liu et al., 2018). It also can be defined as the network robustness as the first approach of resilience, as known as resistance of different hubs. Therefore, two terms for each seaport in the global seaport network are defined, global vulnerability and local vulnerability. Global vulnerability is defined as the share of dominant flow connection within total transport traffic which is an inversely proportional relationship between the number of connections and the distribution of traffic among those connections (Ducruet et al., 2010c, Laxe et al., 2012). Local vulnerability is the climate exposure experienced by the port infrastructures, and population surrounded. It can be known as the stability of the node in the network.

5.2.2. Centrality assessment in maritime transportation

The previous studies state that the importance of a port could be represented by using different centrality indices, including degree centrality, closeness centrality, and betweenness centrality. McCalla et al. analyse the container shipping network and the emergence of transhipment hubs for Caribbean ports (McCalla et al., 2005), and Hu and Zhu study the worldwide maritime transportation network from a complex network perspective (Hu and Zhu, 2009). In 2010, Ducruet et al. analyse the changing position of hub ports in Atlantic regions and Northeast Asia and reveal the changes in traffic in this region by centrality measurements (Ducruet et al., 2010a, Ducruet et al., 2010c), and they try to explore the properties of liner shipping networks and their influence on the evolution of port hierarchies (Ducruet et al., 2010b). In the same year, Kaluza et al. study the spread of invasive species through a complex network of global shipping movements (Kaluza et al., 2010). Then, Ducruet et al. use the centrality assessment again to analyse the relative position of ports in the global network through indicators of centrality in 2012 (Ducruet and Zaidi, 2012). In 2012, Laxe et al. assess changes in the maritime network upon the crisis (Laxe et al., 2012), and Montes et al. compare the way general, and containerised traffic has evolved between 2008 and 2011 (Montes et al., 2012). In 2015, Li et al. divides global shipping into 25 areas from geographical perspective to present an analysis of each shipping area's position in the GSN through indicators of centrality (Li et al., 2015), and evaluate the accessibility and connectivity of the main Canarian ports (Tovar et al., 2015). In 2016 and 2019, there were two studies to analyse the port connectivity and centrality of the Maritime silk road (Zong and Hu, 2016, Wu et al., 2019). In 2018 Liu et al. carried out an analysis of vulnerabilities in maritime supply chains by centrality assessment.

From the previous literature, centrality assessment is joint for understanding the centrality of seaports. Therefore, centrality assessment is chosen for assessing the centrality of major port cities for understanding the connectivity of the whole global shipping network.

5.2.3. Climate vulnerability assessment for coastal cities

There are various studies for different climate change vulnerabilities and increasing trends in climate change adaptation areas (Poo et al., 2018a), we observe a growing number of climate vulnerability studies for both critical transportation infrastructures (Chhetri et al., 2015, Hua et al., 2012, Hunter et al., 2003, Repetto et al., 2017, Sánchez-Arcilla et al., 2016, Sierra et al., 2016, Sierra et al., 2017a, Testut et al., 2006) and coastal regions (Abou Samra, 2017, Akukwe and Ogbodo, 2015, Alsahli and Alhasem, 2016, Briguglio, 2010, Cortès et al., 2018, Djouder and Boutiba, 2017, El-Raey et al., 1999, Genovese and Green, 2015, Graeme and Kathleen, 1999, Gravelle and Mimura, 2008, Hallegatte et al., 2011, Hanson et al., 2011, Hoshino et al., 2016, Kumar et al., 2008, Monioudi et al., 2018, Sterr, 2008, Taramelli et al., 2015, Vitor Baccarin et al., 2016, Yin et al., 2013). They focus on different scales, extreme weather events and social-economic factors. Most of them just focus on specific seaports and port cities, and Hanson et al. and Briguglio provide an international insight for climate vulnerability studies. They analyse the same 136 port cities as they follow the selection by United Nations (Bocquier, 2005). City selection was limited to coastal urban agglomerations with populations greater than one million, which are also recognised port cities, as shown in Annex 6.

The global distribution is concentrated in Asia (52 ports or 38%) with China (14 ports or 10%) and the USA (17 ports or 13%) being the most significant individual countries. The majority are classified as seaports/harbours (119), which includes 16 deep-water ports and two oil terminals. Seventeen river ports in the coastal zone were identified, ranging in size from small (e.g., Hangzhou in China) to very large (e.g., Philadelphia and New Orleans in the USA).

Hanson et al. state a first estimate of the exposure of the chosen 136 port cities to coastal flooding due to sea-level rise and storm surge now and in the 2070s, considering scenarios of socio-economic and climate changes. Meanwhile, Briguglio assesses the climate risk of a population in each territory being harmed by climate change by distinguishing between natural factors and policy-induced factors. Natural factors are associated with inherent climate vulnerability, while policy-induced factors are associated with adaptation. The study juxtaposes indices of vulnerability and adaptation to arrive at an assessment of risk, and finalise four categories of port cities, lowest-risk scenario, managed-risk scenario, mismanaged-risk scenario, and highest-risk scenario. This categorisation gives a solid foundation to the comparative analysis in Section 5.4.5.

5.3. Centrality assessment framework

Two indicators are defined for each seaport in the global seaport network, “global vulnerability” and “local vulnerability”. Based on the definition of graph theory, a network is made up of vertices (also called nodes or points) which are connected by edges (also called links or lines) (Biggs et al., 1986). Global vulnerability is the vulnerability of all links or the whole network, and local vulnerability is the vulnerability of a node. The vulnerability of each independent link is important, but there are limited data for implementing the analysis. The indices and categories set up by Briguglio are used for defining a local vulnerability index for each port (Briguglio, 2010).

To identify the global vulnerability index for each port city, a novel multi-centrality-based indicator is designed by Wu et al. to measure the importance of ports from a more comprehensive perspective. The steps of this study are referenced to the multi-centrality-based indicator study as follows (Wu et al., 2019):

1. Structuring the global shipping network and data collection
2. Modelling of the global shipping network
3. Multiple centrality assessment
4. Validation of the results
5. Comparative analysis for global vulnerability and local vulnerability

5.3.1. Multi-centrality indicator

Three different centralities, representing different characteristics of the port, degree centrality, closeness centrality, and betweenness centrality in a social network (Biggs et al., 1986, Freeman, 1978), make it possible to analyse the relationship between port cities.

Degree centrality is defined as the number of links directly connected to it, which represents the association and importance of that node with other nodes. The larger the degree value of a port, the closer it is to other ports. The parameter can be represented by Equation (5.1):

$$D_{C_i} = \sum_{j}^{n} \delta_{ij} \tag{5.1}$$

where n represents the total number of nodes in the network and δ_{ij} represents the number of edges between i and j.

Closeness centrality represents the sum of the shortest distances from all nodes to a fixed node, which indicates the central location of the node in the network. The larger the closeness centrality value, the easier it is to reach other port destinations within the network. The closeness centrality is between zero and one and can be represented by Equation (5.2):

$$C_{C_i} = \frac{n-1}{\sum_{j}^{n} \delta_{ij}} \tag{5.2}$$

where n - 1 represents the closeness centrality of the network centre point and δ_{ij} represents the shortest distance between the two nodes.

Betweenness centrality measures the extent to which a node is in the “middle” of other “point pairs” in the graph, reflecting the role of the node in the network. As intermediate points that control the connections between these nodes, the betweenness nodes tend to be more powerful. It can be calculated using Equation 5.3:

$$B_{C_i} = \sum_{\substack{s,t \in v \\ s,t \neq i}} \frac{\delta(s,t \mid i)}{\delta(s,t)} \tag{5.3}$$

where, s, t represents a set of node pairs, $\delta(s,t \mid i)$ is the number of times the node pair passes the node i with the shortest distance and $\delta(s,t)$ is the total number of shortest paths between the pair of nodes.

To measure the overall impact of the seaport and rank it according to the summary information of different centrality indicators, this chapter integrates the results from different centrality measures by scoring them using a Borda Count method (Emerson, 2013, Zwicker, 1991). The corresponding score is given according to the ranking order of each candidate as shown in Equation (5.4) to (5.6):

$$S_D(i) = n - Rank_D(i) + 1 \tag{5.4}$$

$$S_C(i) = n - Rank_C(i) + 1 \tag{5.5}$$

$$S_B(i) = n - Rank_B(i) + 1 \tag{5.6}$$

The ranks of degree and closeness consider two directions together, and the three independent scores have equal weights. By obtaining the overall rank, the importance of a port to the global shipping network can be presented, and the overall rank can be presented in Equation (5.7):

$$S_O(i) = S_D(i) + S_C(i) + S_B(i) \tag{5.7}$$

Network efficiency and network average clustering coefficient are chosen indicators to validate the result of the multi-centrality indicator (Ducruet and Zaidi, 2012, Latora and Marchiori, 2001, Liu et al., 2018, Wu et al., 2019). The clustering coefficient of an actor is the density of its open neighbourhood. A graph $G = (P, E)$ consists of a set of vertices P and a set of edges

E between them. An edge e_{ij} connects two vertices, v_i and v_j . The neighbourhood N_i for a vertex p_j is defined as its directly connected neighbours as shown in Equation (5.8). k_i is defined as the number of nodes, N_i of a vertex and $|N_i|$ of a neighbour.

$$N_i = \{v_j : e_{ij} \in E \vee e_{ji} \in E\} \quad (5.8)$$

The local clustering coefficient M_i for a vertex v_i is then given by the proportion of links between the vertices within its neighbourhood divided by the number of links that could exist between them. For a directed graph, e_{ij} is distinct from e_{ji} , and therefore for each neighbourhood N_i there are $k_i(k_i - 1)$ links that could exist among the vertices within the neighbourhood (k_i is the number of neighbours of a vertex). Thus, the local clustering coefficient for directed graphs is given as Equation (5.9), and the network average clustering coefficient is stated as Equation (5.10).

$$M_i = \frac{|\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\}|}{k_i(k_i - 1)} \quad (5.9)$$

$$\bar{M} = \frac{\sum_{i=1}^{n} M_i}{n} \quad (5.10)$$

Network efficiency can be known as average distance or average degree between two nodes. L_{ij} is the distance from node i to j, and the network efficiency is shown as Equation (5.11).

$$\bar{L} = \frac{\sum_{i \neq j} L_{ij}}{n(n-1)} \quad (5.11)$$

As the purpose of this chapter is to evaluate the importance of ports in a shipping network, the nodes are removed one by one. By removing a node from the network and observing the changes, the global influence of a port can be proved. If a node plays an important role in the maritime network in relation to connectivity and stability, removing the node will cause a drastic change in the topology of the whole network, resulting in a rapid reduction in network efficiency and network average clustering coefficient.

5.4. Demonstration of centrality assessment

5.4.1. Structuring the global shipping network and data collection

Structuring the global shipping network is a crucial step to undergo vulnerability assessment, as some seaports are not in the city centres (Pape, 2017). So, a criterion is needed to set up before further investigation: The seaports within a 2-hour circle and 200km travelling distance can be used to represent a traffic flow of the city. The required information is collected from Google map, as shown in Figure 5.1 and 5.2 (Google Maps, 2019). For examples, Tema Harbour is chosen to represent Accra, and Thilawa Port is chosen to represent Yangon. After grouping some sub-urban ports to cities, there are two cities mismatched, Hangzhou and Rabat. By the first criteria, Hangzhou and Rabat can be referenced to Ningbo and Casablanca.

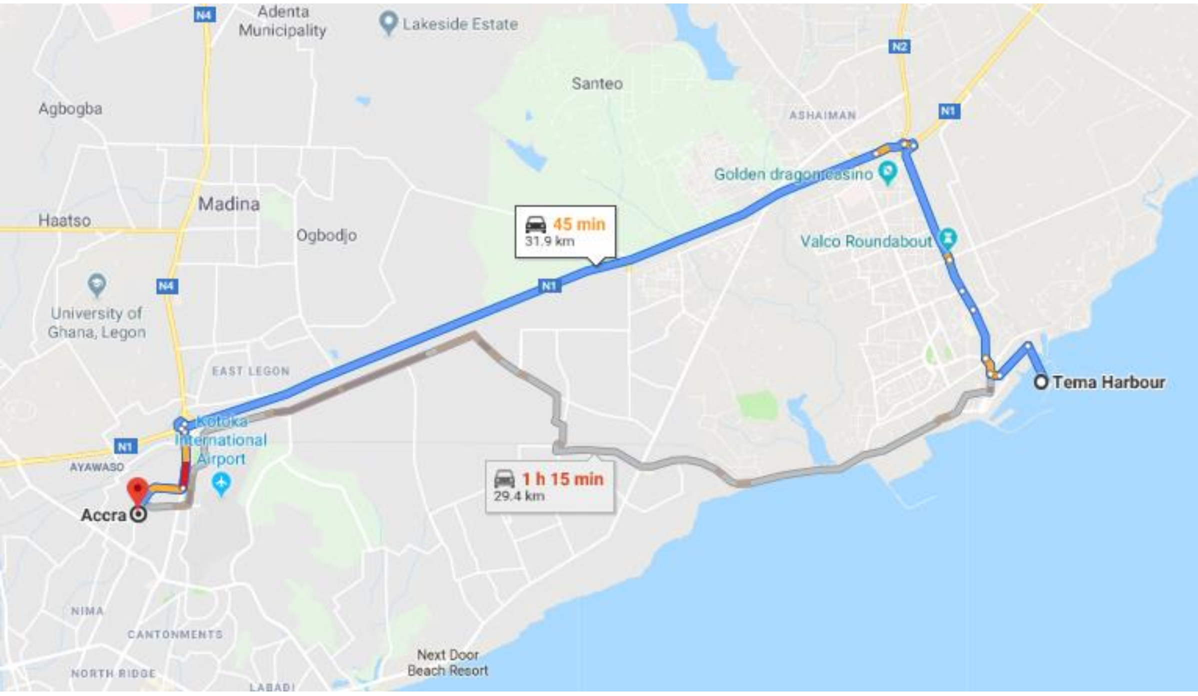

Figure 5.1 Google map recommended travel routes in Ghana

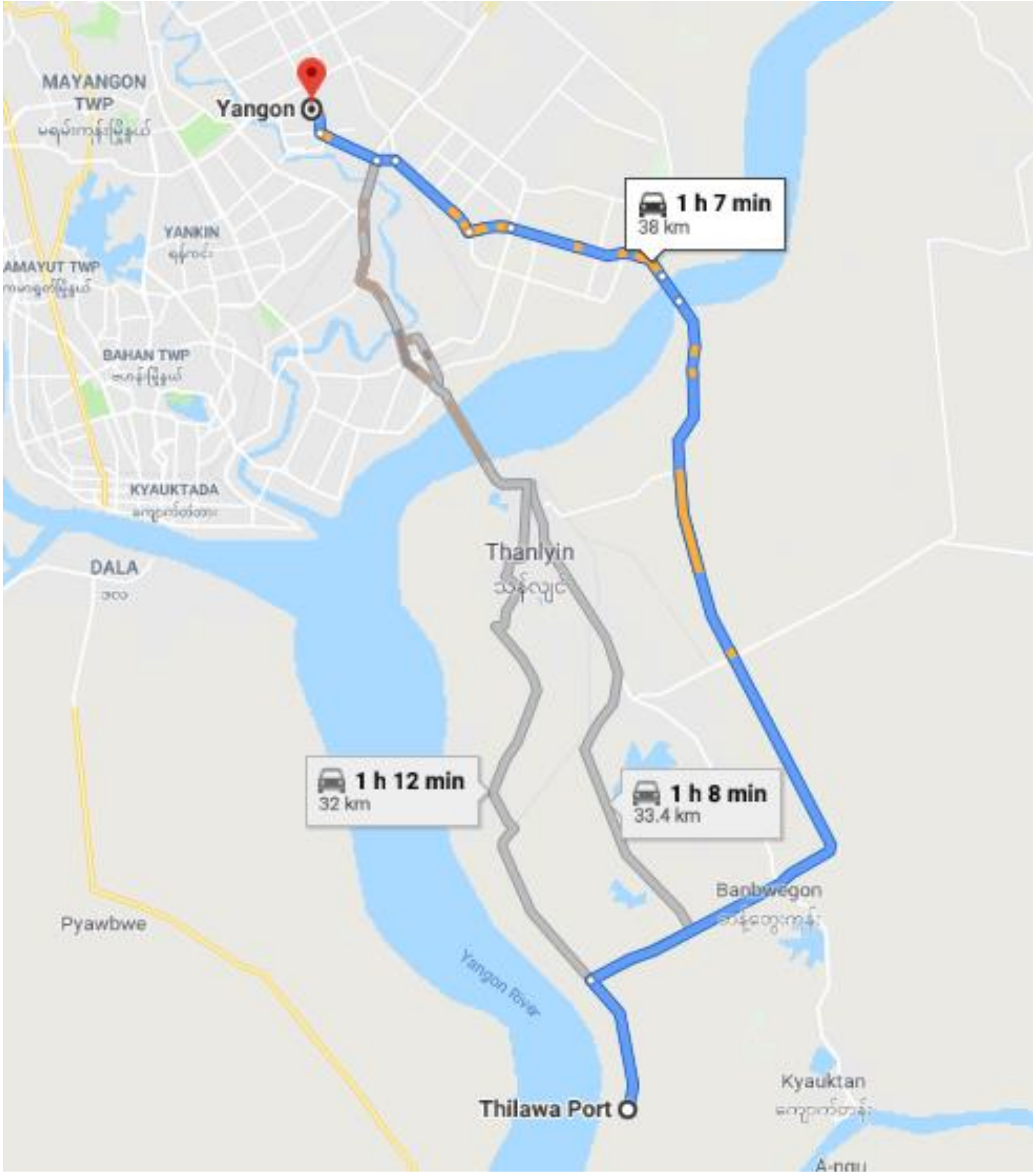

Figure 5.2 Google map recommended travel routes in Myanmar

The data source in our research is from the Maersk shipping line from 12th July 2019 to 31st July 2018 from Maersk website (http://www.maerskline.com). July data is chosen as Baltic Dry Index (BDI) is at the average comparing to other months. BDI in July proves that the activities of the shipping market are ordinary in July. The port cities are chosen for data collection, and twenty transit ports are found between the shipping routes as shown in Annex 7, and six agglomerations cannot locate any routes related to them, they are Dhaka, Belem, Maceio, Natal, Nampo, and Sapporo. So, 2,397 attributes are found between all chosen port cities and transit port cities. Thus, 154-node shipping networks can be formed and modelled.

5.4.2. Modelling of the global shipping network

UCINET 6 for Windows is a software package for the analysis of social network data, and it is chosen for data analysis for this study (Borgatti et al., 2002). To present a network into the tool, an adjacency matrix $A_{n \times n}$ is created, a_{ij} is the attribute or route from i to j. $a_{ij} = 0$ means the service does not exist, and $a_{ij} = 1$ means otherwise. After inputting the data for all values between two nodes, the network can be visualised by the software, as shown in Figure 5.3.

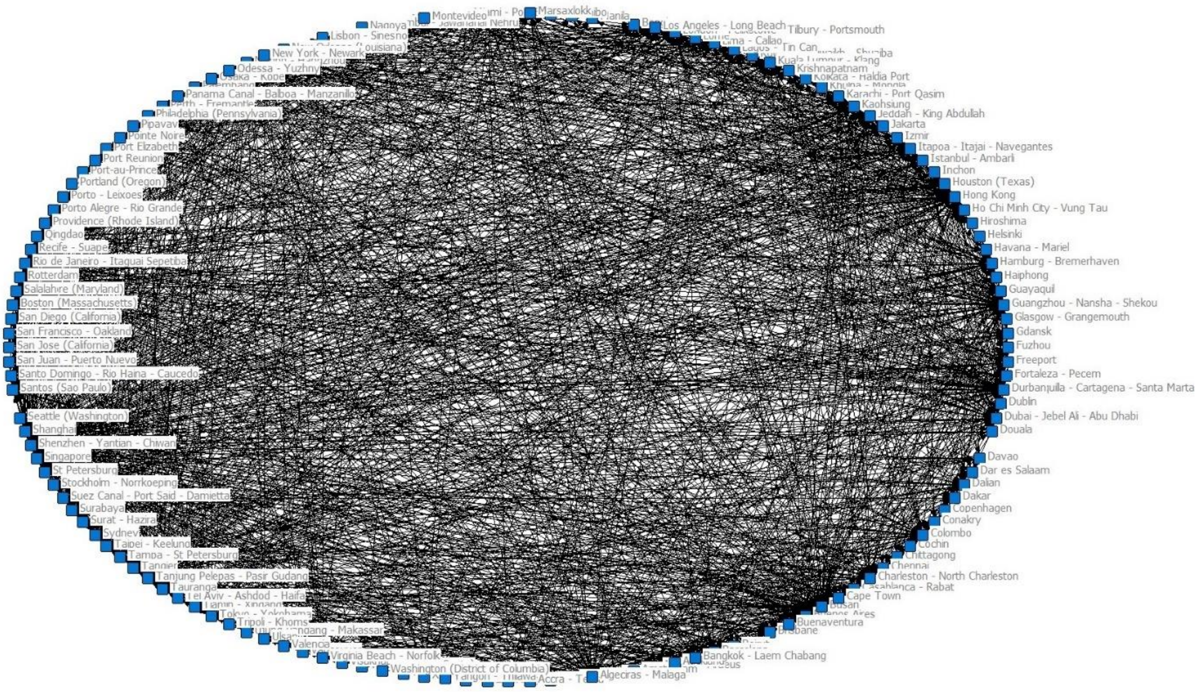

Figure 5.3 Visualization of network

5.4.3. Multiple centrality assessment

The analyses are conducted on degree centrality, closeness centrality, and betweenness centrality independently for the upcoming analysis in Chapter 6. Degree centrality and closeness centrality are directional, and then the two rank sets are based on accumulative values of two directions. Also, additional transit port cities are not included in any ranks. The top 20 ports with these three centralities are listed in Table 5.1.

Table 5.1 Top 20 agglomerations in Relation to Centralities

Rank	**Agglomeration**	**Degree centrality**	**Agglomeration**	**Closeness centrality**	**Agglomeration**	**Betweenness centrality**
1	Shanghai	151	Shanghai	1.302	Singapore	8.919
2	Ningbo	141	Ningbo	1.268	Shanghai	8.629
3	Singapore	133	Singapore	1.218	Ningbo	7.806
4	Busan	114	Busan	1.162	Panama City	6.341
5	Guangzhou	107	Guangzhou	1.152	Busan	6.041

6	Shenzhen	101	Shenzhen	1.142	Rotterdam	5.063
7	Hong Kong	99	Hong Kong	1.114	Hamburg	4.758
8	Qingdao	85	Rotterdam	1.103	Hong Kong	4.542
9	Panama City	83	Qingdao	1.095	Guangzhou	3.687
10	Rotterdam	81	London	1.082	New York	3.479
11	New York	72	Panama City	1.079	Shenzhen	2.661
12	London	67	New York	1.078	Dubai	2.623
13	Hamburg	65	Hamburg	1.060	Qingdao	2.101
14	Dubai	65	Mumbai	1.042	London	1.974
15	Barranquilla	62	Santos	1.041	Barranquilla	1.855
16	Mumbai	62	Dubai	1.040	Baltimore	1.640
17	Santos	61	Barranquilla	1.032	Tianjin	1.598
18	Tokyo	60	Virginia Beach	1.031	Surabaya	1.351
19	Xiamen	59	Miami	1.024	Houston	1.341
20	Tianjin	55	Houston	1.016	Jeddah	1.332
20	Houston	55				
20	Miami	55				
20	Virginia Beach	55				

If some agglomerations have the same values, they will be assigned the highest rank to the set of duplicates. For example, Hamburg and Dubai rank the same for degree centrality. Shanghai has the highest degree of centrality and closeness centrality. Ningbo and Singapore rank second and third places. Singapore scores the highest on the betweenness centrality table and is followed closely by Shanghai and Ningbo. Busan, Guangzhou, Hong Kong, and Rotterdam are in the top 10 in three ranks, and these show their contributions to the global shipping network too. Moreover, the six exempted agglomerations are ranked the lowest. To obtain a final rank for chosen agglomerations, the multi-centrality indicator is implemented, and the ranking is visualised in Table 5.2.

Table 5.2 Top 20 agglomerations of multi-centrality ranking

Rank	**ID**	**Final score**	**Agglomeration**
1	31	461	Shanghai
2	29	458	Ningbo
2	99	458	Singapore
4	93	452	Busan
5	27	444	Guangzhou
6	38	440	Hong Kong
7	28	439	Shenzhen
8	86	437	Panama City
8	82	436	Rotterdam
10	30	426	Qingdao
11	49	425	Hamburg
11	120	425	New York
13	112	418	London
14	110	414	Dubai

15	39	403	Barranquilla
16	57	397	Mumbai
17	12	394	Santos
18	33	390	Tianjin
19	116	389	Houston
20	35	382	Xiamen

More than half of the top 20 agglomerations are from Asia. Then, the other remaining agglomerations are from Europe, Northern America, South America, and Middle East. Five transit port cities have enough scores to rank in the top 20, and they are Tangier, Colombo, Algeciras, Tanjung Pelepas, and Salalah. Global vulnerabilities of all chosen agglomerations are found, and the data set is going to be analysed with the local vulnerability data set.

Table 5.3 Regions of Top 20 agglomerations

Region	**Agglomerations**
North America	New York, Houston
South America	Panama City, Barranquilla, Santos
Europe	Rotterdam, Hamburg, London
West Asia	Dubai, Mumbai
East Asia	Shanghai, Ningbo, Ningbo, Singapore, Busan, Guangzhou, Hong Kong, Shenzhen, Qingdao, Tianjin, Xiamen

5.4.4. Validation of the results

Network efficiency and network clustering coefficient are used to validate the result of multi-centrality ranking as mentioned in Section 5.4.3. The top 20 agglomerations shown in Table 5.2 are taken away from the network one by one to observe the changes as shown in Figure 5.4. The agglomerations are listed from left to right according to their rank. The drops in both indicators are significant for Shanghai, Singapore, and Ningbo. The changes in network cluster coefficients are from 2.090% to 3.284%, and those of network efficiency are from 0.832% to 1.313%. After that, the network cluster coefficient decreases gradually from the fourth to twentieth, and network efficiency does not have many changes as those changes are not more than 0.788%.

Even the sequences of network efficiency and network cluster coefficient are not the same, they still can show the same factors as the higher the multi-centrality rank, the higher the importance to the global shipping network. Therefore, the multi-centrality ranking is validated, and the result can be used to analyse local vulnerability data in the next section.

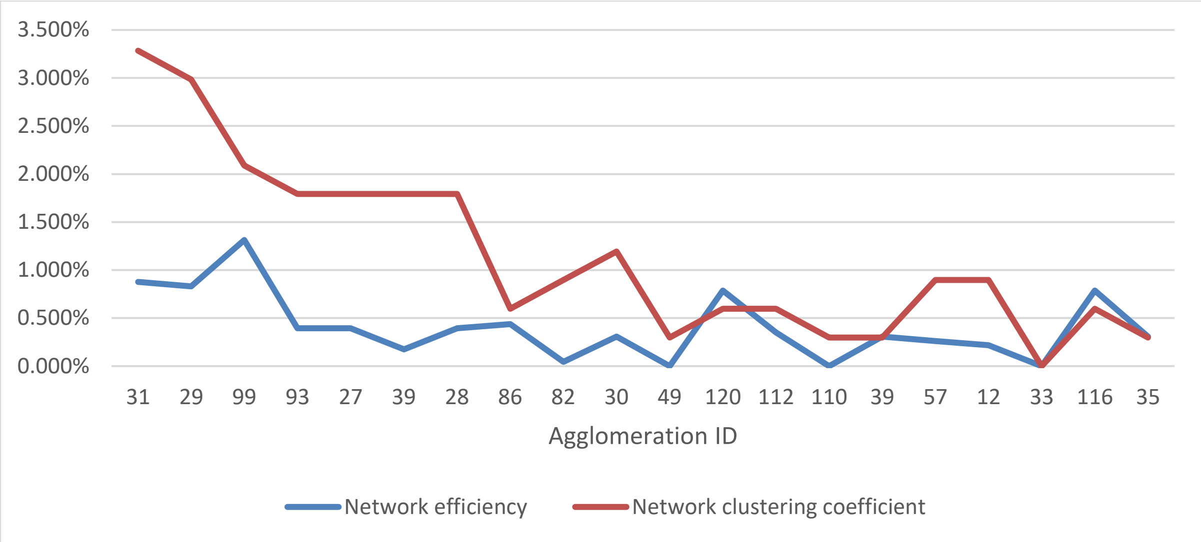

Figure 5.4 Drop of network efficiency and network clustering coefficient by removing an important agglomeration

5.4.5. Comparative analysis for global vulnerability and seaport vulnerability

To understand the climate change influences on the global shipping system in an comprehensive way, global vulnerability and seaport vulnerability are introduced to observe the difference between the influences inside and outside a port city. The indices and categories set up by Briguglio are used for defining the local vulnerability index for each agglomeration (Briguglio, 2010). He refers to the finding from Nicholls et al. (Nicholls et al., 2008) on climate vulnerability and the data from United Nations Conference on Trade and Development (UNCTAD) on GDP per capita index, assumed to proxy adaptation measures (UNCTAD, 2007). By juxtaposing them, therefore the extent of risk of the effects of climate change can be assessed.

It can be found that 32 port cities are in the "lowest-risk" category, and these are mostly port cities in high-income countries. In total, 27 port cities are in the "managed-risk" category. They are vulnerable cities, mostly located in high-income countries. About 38 cities are located in the "mismanaged-risk" category, and these are low-vulnerability cities, mostly in low-income countries. The remaining 39 cities are the "highest-risk" countries, with high-vulnerability cities located in low-income countries. The result is stated in Annex 6.

Multi-centrality ranking is implied to all agglomerations. For the six port cities without any connection, Dhaka, Belem, Maceio, Natal, Nampo, and Sapporo, they rank the lowest in every single-centrality ranking, and thus the final one. Then, Hangzhou and Rabat are referenced to the result of Ningbo and Casablanca. The full comparative analysis is shown in Table 5.4.

Table 5.4 Multi-centrality scoring and ranking of four local vulnerability categories

Category	**Number of members**	**Number of top 20**	**Total score**	**Average score**	**Total rank**	**Average rank**
Lowest-risk (1)	32	1	5476	171.125	2547	79.594
Managed-risk (2)	27	8	6919	256.259	1344	49.788
Mismanaged-risk (3)	38	3	6729	177.079	2645	69.615
Highest-risk (4)	39	8	8441	216.436	2473	63.410

There is just one port city of Category 1 in the top 20, and the average rank of Category 1 port cities are the lowest throughout all four categories. The only top 20 agglomeration of Category 1 is Singapore. On the other hand, there are eight port cities of Category 4 in the top 20, and the average rank of Category 4 port cities are the second highest. The top 20 agglomerations of Category 4 are from China and India. Therefore, some findings can be stated. Global vulnerabilities do not distribute as local vulnerabilities. Some important highest-risk port cities should put more efforts into climate change adaptation. Also, some lowest-risk port cities can take more critical positions in the global shipping network.

5.5. Discussion

By defining global and local concerns on the global shipping network, the discussion can be split in two directions. Local vulnerability has attracted more research interests in the past century (Poo et al., 2018b). More tailor-made adaptation plans for port cities should be designed for both high-income and low-income port cities. Also, climate change will have profound impacts on urban infrastructure systems and services, the built environment, and ecosystem services and hence on urban economies and population. It could exacerbate existing social, economic, and environmental drivers (IPCC, 2014a). If the vulnerability assessment is considered in the scale as mentioned by the Intergovernmental Panel on Climate Change (IPCC), agglomerations need to experience warming trend, extreme temperature, drying trend, extreme precipitation, snow cover, damaging cyclone, sea-level rise, and flooding. Therefore, a more comprehensive international vulnerability assessment can be designed to assess the local vulnerability through the global shipping network. The Germanwatch organisation has promoted some similar indices for global climate risks (Eckstein et al., 2018). It is on the national scale, so some detailed assessments are needed for port cities and global shipping network.

Global vulnerability is as crucial as local vulnerability. For the route between two ports, weather routing is suggested to provide the recommendations on transportation routes prior to and during ship sailing in various navigation constraints under global weather forecasts. Local vulnerability is possible to be reduced by new technologies. But for the network robustness, it is essential to enhance the resilience of the network. By observing the properties of network efficiency and network clustering coefficient in Section 5.4.4, decentralisation is possible to increase the system reliability, scale, and privacy (Kimbu and Ngoasong, 2013, Quinn et al., 2006). Therefore, lowest-risk agglomerations mentioned in Section 5.4.5 should contribute more to the global shipping network. However, "Geography is destiny" (Eichengreen, 1998). Some port cities are important because of high populations and trades, such as Shanghai and New York. Also, straits and canal are crucial for cargo transhipment, and Singapore and Panama City are very essential port cities for global shipping and world trade. The changes in "geography" may be possible to reduce the vulnerability of the shipping network. Arctic shipping routes that have historically been covered by sea ice become navigable for part of the year (Ng et al., 2018), and lowest-risk port cities include some high latitude port cities, Montreal, Helsinki, Sapporo, Ulsan, Stockholm and Glasgow. Therefore, new shipping routes can make them more critical and decentralise the world shipping network. Also, building up a new canal is a way to reduce the reliance on the existing straits and canals. The Nicaragua canal can bear the workload and importance of the Panama Canal (Bailey, 1936, Chen et al., 2019), and the Kra Canal can connect the Gulf of Thailand and Bay of Bengal (Ronan, 1936, Sulong, 2012). Some new crucial port cities will take shape if the canals are constructed. By enlarging the shipping network, it can be still considered as decentralisation.

This chapter provides insights into the climate vulnerability of the global shipping network with different perspectives. The main lesson that can be drawn from this chapter is that being highly vulnerable globally is different from being locally vulnerable. Therefore, more comprehensive local climate vulnerability assessments are needed to be done. Also, a city includes intermodal transport infrastructures, and the network robustness study needs to be applied on some other transportation modes. On the other hand, a more comprehensive global vulnerability study can be done. It can focus on different regions and shipping companies, and it can include fleet capacity and economy profit for centrality analysis. Also, it provides the top 20 seaport cities, twenty seaports with highest centrality in the global shipping network, for case study in the next chapter by shipping routing model.

Chapter 6 Shipping routing model

6.1. Summary

Chapter 6 formulates the routing problem of the global shipping network constructed for climate resilience. A shipping network model has been designed to find the optimum shipping route between ports, and changes on route selections based upon more port disruption days caused by extreme weather. Artificial Bee Colony (ABC) algorithm is used to optimise the performance of the model.

This chapter first provides a critical review of port disruption due to climate extremes, multiple-objective decision support for environmental sustainability in the maritime industry, and ABC algorithm for vehicle routing problem (VRP) and supply chain management (SCM) in Section 6.2. Second, the problem formulation and solution methodology of the shipping routing model in Section 6.3 and Section 6.4. Third, a numerical experiment is done in Section 6.5, followed by computation result by the designed shipping routing model in Section 6.6. Fourth, climate resilience assessment is done with the top 20 seaports and with the whole global shipping network in Section 6.7. Finally, a discussion with research implication is shown in Section 6.8.

6.2. Review for shipping routing model

Globally, the awareness for climate change and urbanisation is growing, as their consequences become increasingly apparent. 40% of the global population lives within 100 km of the coast, and port cities are significant concentrations for a population with 13 out of the 20 most populated cities in the world in 2005 being port cities. Extreme weather events, supercharged by climate change, affected some 62 million people around the world in 2018 (United Nations, 2019). Besides, these cities form a vital component of national and global economies, particularly in developing countries, with a global tripling in the volume of seaborne trade over the past 30 years (Becker et al., 2013).

Port cities are also exposed to the risk of the impacts of climate variability and change, particularly given their location in coastal zones, low-lying areas and deltas. Extreme weather events can cause failures in different ports, and the shipping network may suffer a cascading breakdown. Therefore, climate vulnerability assessments are not enough just focusing on seaports, known as nodes, independently. Also, a network vulnerability study for a global shipping system is needed to test the network resilience from failures in different seaports (Berle et al., 2011, Gonzalez Laxe et al., 2012).

Vulnerability and resilience are two crucial concepts in the literature on hazards and climate change but have been used in a variety of ways to investigate human interaction with a hazardous environment (Joakim et al., 2015). "Vulnerability" can be defined as a threshold, exposure to a hazard, pre-existing condition, or an outcome after adaptation. On the other hand, resilience can be defined as resistance, recovery, creative transformation. A literature review on maritime vulnerability and resilience reveals that there are two research challenges from the previous studies. First, the definition of vulnerability and resilience are not stable in the maritime or climate change sector (Thomas et al., 2019). Second, the previous climate vulnerability assessments are just focusing on the risk within a single port or a single route (Poo et al., 2018b). To fill this research gap, a comprehensive centrality assessment on the global seaport network takes place. Then, the result is put together with another result of an in-port climate risk assessment for comparative analysis.

6.2.1. Port disruption due to climate extremes

Considering a full coverage of risks, Chopra and Sodhi classify supply chain risks into nine categories: Disruptions, delays, systems, forecast inaccuracies, intellectual property breaches, procurement failures, system breakdown, inventory, and capacity issues (Chopra and Sodhi, 2004). Hurricane Lorenzo, the most potent eastern Atlantic storm ever recorded, hit the UK and Ireland in October 2019 and sunk a tugboat carrying fourteen crew members (Fedschun, 2019). Seaports are in areas vulnerable to climate change impacts: on coasts susceptible to sea-level rise and storms or at mouths of rivers susceptible to flooding (Becker et al., 2012). On the other hand, extreme and continuous heat can also damage road surfaces and distort rail lines (Sieber, 2013), and it affects the land transport connectivity of seaports. So, climate extremes should be considered as one important factor to analyse port disruption (Lam and Su, 2015).

Hubbert and Mclnnes develop a storm surge inundation model to assess coastal flooding resistance (Hubbert and Mclnnes, 1999). Then, Ronza et al. evaluate the economic damage originated by major accidents in port areas (Ronza et al., 2009). In 2011, Hanson et al. provide a comprehensive study to compare the performance of large port cities when facing sea-level rise risks (Hanson et al., 2011), and Hallegatte et al. assess climate impacts, sea-level, and storm surge risk in Copenhagen (Hallegatte et al., 2011). In 2015, Genovese and Green assess the storm surge damage to coastal settlements in Southeast Florida (Genovese and Green, 2015). Akukwe and Ogbodo propose a spatial analysis of vulnerability to flooding in Port Harcourt Metropolis, Nigeria (Akukwe and Ogbodo, 2015). In 2016, Vitor Baccarin et al. present a climate change vulnerability index and case study in a Brazilian coastal city (Vitor Baccarin et al., 2016), and Hoshino et al. estimate the increase in storm surge damage due to climate change and sea-level rise in the Greater Tokyo area (Hoshino et al., 2016). Alsahli and Alhasem assess the sea-level rise vulnerability of the Kuwait coast, and Zhang and Lam estimate the economic losses of port disruption by extreme wind events (Zhang and Lam, 2015). Djouder and Boutiba set up a vulnerability assessment of coastal areas to sea-level rise from the physical and socioeconomic parameters at Gulf of Bejaia, Algeria (Djouder and Boutiba, 2017), and Abou Samra uses cartographic modelling to assess the impacts of coastal flooding, with a case study of Port Said Governorate, Egypt (Abou Samra, 2017). Then, Cortès et al. implement the flood risk assessment in Mediterranean urban areas, with the case of Barcelona (Cortès et al., 2018).

Many scholars give highlights on individual climate vulnerability assessments. However, the whole shipping network has not yet been assessed with a focus on environmental sustainability. Therefore, a global shipping network is preferable to be assessed by comparison on vessel routing selection under different climate risks, as known as the port disruption days in the future. An optimisation model as a decision support system (DSS) on the routing problem can be introduced to solve the problem.

6.2.2. Multiple-objective decision support for environmental sustainability in maritime industry

Sustainability has become a significant influence in designing the organisational business models (Sarkis et al., 2013). In 2015, Mansouri et al. finish a literature review to examine the potential of multi-objective optimisation (MOO) as a DSS (Mansouri et al., 2015). There are fifty-two journals in total, and three categories on maritime shipping are set up: Environmental sustainability, DSS, MOO. Environmental sustainability in maritime shipping is a vital attribute of the literature review. DSS is commonly considered to be implemented for maritime business (Fagerholt et al., 2009, Lam, 2010). MOO is the optimisation in maritime shipping (Finkelstein et al., 2009, Kollat and Reed, 2007). There are forty studies in environmental sustainability, twelve in DSS, and fourteen in MOO, including overlaps. There are 14 overlapped studies, which are crucial to notice the possibilities to initiate MOO-based DSS for sustainability in maritime shipping.

There are five studies for inventing DSSs to enhance sustainability in maritime shipping and eight studies on sustainability trade-offs in maritime shipping. Also, there is one study on

MOO-based DSS in marine shipping. Ballou et al. develop a DSS to support optimised ship operation including the vessel's hull design, propulsion system, seakeeping models and a safe operating limit for reducing fuel consumption and green house gases (GHG) emissions. (Ballou et al., 2008). Balmat et al. implement a risk assessment in maritime shipping regarding safety at sea with a focus on pollution prevention on the open sea (Balmat et al., 2011). Windeck and Stadtler develop a DSS for designing liner shipping networks by considering environmental factors and minimising cost and CO2 emissions (Windeck and Stadtler, 2011). Bruzzone et al. present a simulator for assessing the environmental impact on port operations. Balmat et al. propose a fuzzy framework for the maritime risk assessment for safety and oil pollution prevention at sea (Balmat et al., 2009). Palacio et al. determine container depots for minimising the total cost of the network and the environmental impact of the depots and their associated delivery operations (Palacio et al., 2016). Chen et al. propose a model for optimising truck arrival patterns at marine container terminals to reduce emissions from idling truck engines by minimising both trucks waiting times and arrival pattern changes (Chen et al., 2013). Qi and Song optimise vessel scheduling considering uncertainty in port availability and frequency requirements on the liner schedule, considering service level and fuel consumption (Qi and Song, 2012). Brouer et al. present the vessel schedule recovery problem (VSRP) to evaluate a given disruption scenario and to select a recovery action that balances the trade-off between increased bunker consumptions and the impact on service levels (Brouer et al., 2013). Hu et al. present a model for allocating the berth and quay-cranes to vessels by minimising fuel consumption and emissions of the vessels (Hu et al., 2014). Song and Xu compare CO2 emissions from direct and feeder liner services in the case of Asia–Europe Services; also they develop an operational activity-based method for estimating CO2 emissions from shipping networks (Song and Xu, 2012a, Song and Xu, 2012b). Corbett et al. analyse policy impacts of a fuel tax and a speed reduction mandate on CO2 emissions by applying a profit-maximising equation to estimate route-specific speeds which are economically efficient (Corbett et al., 2009). Grabowski and Hendrick assess the trade-offs between shipboard safety and crew size (Grabowski and Hendrick, 1993).

Simulation optimisation is one of the promising approaches to address the resultant problems in maritime transportation. This is one of the significant gaps in the literature that needs further research and development, and MOO based DSS for improving the sustainability of the maritime supply chain. For assessing the impacts of port disruption due to climate extremes on global shipping networks, an ABC algorithm is favourable for imparting into a MOO model to find a heuristic solution as the global shipping network is always vast with many solutions (Mansouri et al., 2015).

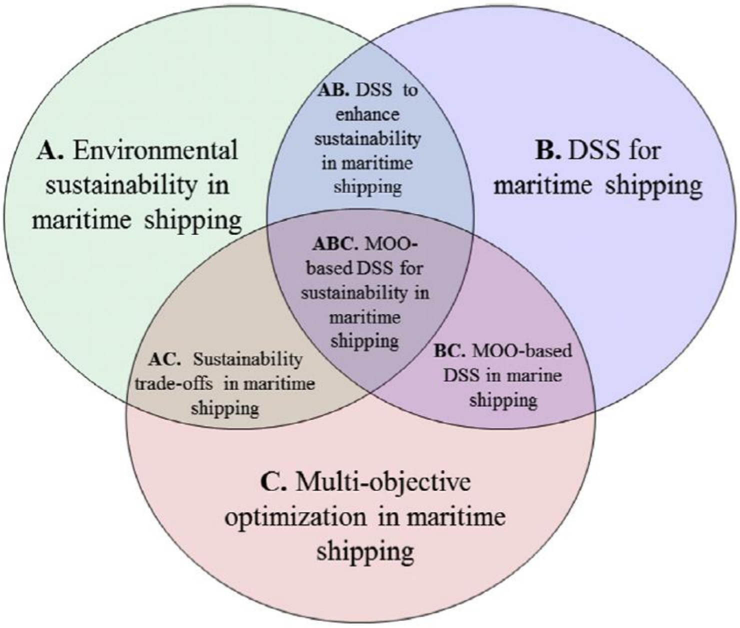

Figure 6.1 The scope of the literature review for multiple-objective decision support for environmental sustainability in maritime industry

6.2.3. Artificial Bee Colony Algorithm for vehicle routing problem and supply chain management

The ABC algorithm simulating the foraging behaviour of honey bees was invented by Karaboga (Karaboga, 2005). Among different swarm intelligence (SI) algorithms mentioned, ABC is one of the algorithms based on bee swarms which has been most widely studied and applied to solve real-world problems, so far (Karaboga et al., 2014). One of the primary applications is the vehicle routing problem (VRP) with different constraints, including vehicle capacities and carbon emissions. From 2011 to 2014, three studies were working on the capacitated vehicle routing problem (CVPR) by ABC algorithm (Brajevic, 2011, Szeto et al., 2011, Gomez and Salhi, 2014). Then, three enhanced versions of the artificial bee colony heuristic are also proposed to improve the solution qualities of the original version. Afterwards, time constraint is imparted to the CVPR (Ji and Wu, 2011, Shi et al., 2012, Yao et al., 2013), and there are case studies on public bike repositioning (Shui and Szeto, 2015) and green vehicle routing with cross-docking (Yin and Chuang, 2016). A vehicle is a machine that transports people or cargo.

SCM is being adopted as the most efficient way of managing operations in an enterprise, and organisations deploying supply chain systems are globally on the rise. The main objective of SCM is establishing the highest coordination between all the entities of the network. Swarm Intelligence (SI) techniques have been applied to the realm of SCM in the following significant areas (Soni et al., 2019):

- Distribution network design;
- Supplier management;
- Inventory optimisation;
- Vehicle routing; and
- Resource allocation.

Except for VRP, ABC has been applied to different sectors in SCM. After 2010, eleven studies are imparting ABC algorithm on shipping logistic problems. Kumar et al. minimise the supply chain cost with embedded risk using computational intelligence approaches (Kumar et al., 2010). Pal et al. use the ABC algorithm to solve an aggregated procurement, production, and shipment planning decision problem for a three-echelon supply chain (Pal et al., 2011), and Taleizadeh et al. propose a hybrid method of ABC fuzzy simulation to optimise constrained inventory control systems with stochastic replenishments and fuzzy demand (Taleizadeh et al., 2013). Then, Zhang et al. develop a mixed-integer nonlinear programming (MINLP) model to design supply chains (Zhang et al., 2016). Kefer et al. use the fuzzy multi-criteria proposed ABC classification method (Kefer et al., 2016), and Gökkus and Yildirim compute a container traffic forecasting model by ABC (Gökkus and Yildirim, 2017). In 2017, Zeng et al. present a metaheuristic model for gantry crane scheduling and the storage space allocation problem in railway container terminals, and Zhu et al. optimise a shipping model by ABC (Zhu et al., 2017). In 2018, Sumner and Rudan propose a hybrid MCDM approach to transhipment port selection (Sumner and Rudan, 2018), and Zhang et al. develop a mixed-integer linear programming model to obtain the optimal repositioning of empty containers through the intermodal transportation network. In 2019, Poo and Yip propose an optimisation model for container inventory management, and Wang et al. constructs a three-level marine logistics network site-distribution model based on the low-carbon scenario (Wang et al., 2019).

By understanding the use of ABC in VPR and SCM, ABC can solve routing problems on a global scale. An advanced ABC model is used for integrating the climate change impacts to assess the impacts of port disruption and the climate resilience on the global shipping network.

6.3. Problem Formulation

6.3.1. Notations

The following notations are adopted in the following mathematical model.

Sets:

N	Set of ports;
K	Set of transhipments, including no transhipment;

Indices:

i, j	Indices of nodes;
k	Indices of transhipment stages;
a	Indices of starting port;
b_k	Indices of transhipment port;
c	Indices of ending port;

Parameters:

Z	Total time;
Z_{ij}	Total time from port i;
T_{ij}	Travel time from port i to port j;
TT	Total travel time
S_i	Service time at port i;
ST	Total service time;
S_i^b	Basic service time at port i;
I_i	Risk of a territory being affected by climate change (CR in Annex 6 and Annex 7);

M Very large positive constant;

Decision variables

x_{ij} 1 if directly travels from port i to port j; 0 otherwise;

ϕ_i Auxiliary variable associated with port i used for the sub-tour elimination constraint;

6.3.2. Formulation

$$Z=\sum_{i\in N}\sum_{j\in N\setminus\{i\}} z_{ij} \tag{6.1}$$

$$z_{ij}=\min_{k\in K}\left(TT_{ij,k}+ST_{ij,k}\right) \qquad \forall i\in N,\ j\in N\setminus\{i\} \tag{6.2}$$

subject to

$$TT_{ac,k}=T_{ab_1,k}+T_{b_1b_2,k}+T_{b_2b_3,k}+\ldots+T_{b_kc,k} \qquad \forall a,b_1,b_2,\ldots,b_K,c\in N \tag{6.3}$$

$$ST_{ac,k}=S_{a,k}+S_{b_1,k}+S_{b_2,k}+\ldots+S_{b_k,k}+S_{c,k} \qquad \forall a,b_1,b_2,\ldots,b_K,c\in N \tag{6.4}$$

$$S_i^b=S_i\times I_i \qquad \forall a,b_1,b_2,\ldots,b_K,c\in N \tag{6.5}$$

$$\sum_{j\in N\setminus\{i,a,c\}} x_{ij}\le 1 \qquad \forall i\in N\setminus\{a,c\} \tag{6.6}$$

$$\sum_{i\in N\setminus\{j,a,c\}} x_{ij}\le 1 \qquad \forall i\in N\setminus\{a,c\} \tag{6.7}$$

$$x_{ij}\in\{0,1\} \qquad \forall i\in N\setminus\{a,c\},\ j\in N\setminus\{i,a,c\} \tag{6.8}$$

$$x_{ii}=0 \qquad \forall i\in N\setminus\{a,c\} \tag{6.9}$$

$$\phi_j=\phi_i+1-M\left(1-x_{ij}\right) \qquad \forall i\in N\setminus\{a,c\},\ j\in N\setminus\{i,a,c\} \tag{6.10}$$

$$\phi_i\ge 0 \qquad \forall i\in N\setminus\{a,c\} \tag{6.11}$$

6.3.3. Equations Explanation

Equation (6.1) is the objective function of the problem, which is the total time of all delivery routes between the set of ports. Equation (6.2) represents the objective function of each single route, and the two components are travel time and service time. Constraint (6.3) defines the total travel time between the starting node, the k transhipment nodes, and ending node. Constraint (6.4) defines the total service time between the starting node, the k transhipment nodes, and ending node. Constraints (6.5) define service time of a node based on the climate performance index. Constraints (6.6) and (6.7) limit each node to being visited at most once in each period. Constraint (6.8) states the routing decision variables to be binary. Constraint (6.9) ensures no inter-ship activity within the same port. Constraint (6.10) is the sub-tour elimination constraints. Constraint (6.11) ensures that the auxiliary variables are non-negative.

6.3.4. Assumptions

There are multiple possible solutions for minimizing Z, known as the accumulated shortest paths between all nodes. Several features take place after implementing the following assumptions:

- The service time in the transhipment node is fixed, independent of cargo loading and unloading times;
- The travel time between the starting node, transhipment nodes, and ending node is fixed;
- The minimum service time is one day;
- Port disruption implies a static delay and is represented in basic service time.

6.4. Solution Methodology

In Section 6.3, program formulations have been set up and can be used to solve the shipping routing problems (Poo and Yip, 2019). For optimising the performance, the heuristics method is suitable to sort out the best solution within many possible solutions. Artificial Bee Colony (ABC) algorithm is applied to find heuristic solutions.

6.4.1. Artificial Bee Colony Algorithm

In the ABC Algorithm, a food source (solution) has fitness. The “bees” are going to find out a food source with a food source as fit as possible. There are three key steps or types of “bee” in the whole algorithm: employed bees, onlooker bees and scout bees (Karaboga, 2005).

The value, or say the quality, of a food source, depends on two factors, which are travel time and service time. For the sake of simplicity, a single quality is used to represent a food source. Employed bees are associated with a food source which they have been recently exploiting. They grab the information of the source and share the information with the probability of profit.

Onlooker bees are waiting in the nest and establishing food sources by receiving the information shared by employed bees. Scout bees are searching the whole search area for new food sources randomly.

One part of the colony consists of "employees", and the other part consists of "onlookers". For every food source, there is only one employed bee. The employed bees whose food source has been exhausted by the bees will convert to be a scout. The full main idea can be stated below:

Send the scout bees to random initial food sources

REPEAT

Send the employed bees to the food sources and check their fitness

Calculate the probability of the sources whether the sources are preferred by onlooker bees

Send the onlooker bees to the food sources and check their fitness

Stop the exploitation step of the sources which have been exhausted by the bees

Send the scout bees to the search area for searching for new food sources

Memorize the best food source

UNTIL (meeting specific requirements)

Based on the basic idea of ABC, the steps of the ABC algorithm are summarized as follows:

1. Generate a set of solutions randomly as initial food sources wi, i = 1,…,π. Assign each employed bee to a food source
2. Evaluate the fitness $f(x_i)$ of each of the randomized food sources w_i, $i = 1,\dots,\pi$
3. Set a counter, $z = 0$ and limitation of food sources (solution), $w_1 = w_2 = \dots = w_\pi = 0$
4. REPEAT
    a. Employed Bee Phase
        i. For each food source x_i, enforce a neighbourhood operator, $x_i \rightarrow x^*$
        ii. If $f(x_i) > f(x^*)$, substitute x_i by x_i^* and $l_1 = 0$. Otherwise, $w_1 = w_1 + 1$
    b. Onlooker Bee Phase
        i. For each food source xi, undergo the fitness-based roulette wheel selection method.

ii. For each food source xi, enforce a neighbourhood operator, xi → x#

iii. If f(xi) > f(x#), xi is substituted by x# and li = 0. Otherwise w1= w1 + 1

c. Scout Bee Phase

i. For each food source xi, wi = Limit, xi is substituted by a randomly generated food source

ii. $z = z + 1$

5. UNTIL (Reaching Operation Cycle)

After figuring out the idea of ABC, the solution representation and neighbourhood operators must be introduced to make the shipping route problem fit the ABC algorithm. This is enhanced by an ABC shipping network modelling for container inventory management.

6.4.2. Solution Representation

To apply the ABC, identifying the food source, solution, is a must for the bees throughout the whole algorithm. z(x) is set up as the cost function of the whole delivery process. First, the solution is represented in the form of a vector with a length of (starting port + transhipments + ending port). A sequence should start and end with 0, which denotes the starting point, to simulate the port travelling from starting to visit the ports. Consider a delivery route with seven transhipment ports, with Port 13 and Port 34.

13	15	24	46	38	7	91	116	34

Figure 6.2 Solution representation

The ship passes through 13→15→24→46→38→7→91→116→34. Then, an initial solution is generated by putting the ports into the solution vector accordingly. Then the sequence will be shuffled several times. The shuffling time is equal to half of the number of ports. A total of τ solutions are generated during initialization. Then, a neighbourhood operator is used to find out new solution $X^{\#}$ from the current solution X_i. A neighbourhood operator will be further explained in the next part.

6.4.3. Neighbourhood Operators

A neighbourhood operator is used to find out new solution $X^{\#}$ from the current solution X_i. A neighbourhood operator will be chosen from the pre-selected neighbourhood operators and applied for one time. Except for the first period, the port after 0 is prevented from being moved as it is the last port of the previous period. The shaded position is under operation.

Three neighbourhood operators are chosen to put in my program for random selection:

- Random swaps

The operator randomly chooses two positions, i and j with i ≠ j and exchanges the positions.

Before:

13	15	24	46	38	7	91	116	34

After:

13	15	91	46	38	7	34	116	34

Figure 6.3 Example of random swap

- Reversing a sub-sequence

The operator randomly chooses a sub-sequence and reverses it.

Before:

13	15	24	46	38	7	91	116	34

After:

13	15	24	46	38	116	91	7	34

Figure 6.4 Example of reversing a subsequence

- Random swaps of reversed sub-sequence

The operator randomly chooses two sub-sequences and swaps them. Then each of the swapped sub-sequences has a chance to be reversed with a 50% probability. The length of sequence has been limited to 3.

Before:

13	15	24	46	38	7	91	116	34

After:

13	15	91	116	38	7	24	46	34

Figure 6.5 Example of random swaps of reversed subsequence

For exploring the whole solution sets, scout bee takes places to rearrange the sequence. A new node is created by shuffling the sequence.

Before:

13	4	24	46	38	7	91	116	34

After:

13	97	3	113	23	9	98	117	34

Figure 6.6 Example of shuffling

6.4.4. Fitness Evaluation

In every period, each onlooker chooses a food source randomly. In order to drive the choosing process towards a better solution, the roulette-wheel selection method is implemented for randomly choosing a solution by setting the fitness value of each bee inversely proportional to the cost function value. The probability of choosing the solution Xi is then stated as:

$$p(X_i) = \frac{z(X_i)}{\sum_{j=1}^{\tau} z(X_j)}, i = 1,2, \dots, \tau$$

6.5. Numerical Experiment

For parameter setting, the bee colony size was set to be 50, and the numbers of employed bees and onlooker bees were equal to half of the bee colony size (i.e., 25 for each), which can help on reducing parameters when conducting the program including the algorithm (Karaboga and Basturk, 2007). 25 employed bees represent that 25 routes are recently exploited, and 25 onlooker bees represent that 25 routes are established by receiving information from "employed bees".

6.5.1. Network Settings

Structuring the global shipping network is the first step building up the global shipping network. 136 large port cities, the population exceeding one million inhabitants in 2005, are chosen to be a part of the network and they are shown in Annex 6, and the further setting procedures

The travel time in our research is from the Maersk shipping line from 12th July 2019 to 31st July 2019 from Maersk website (http://www.maerskline.com). The port cities are chosen for data collection, and twenty transit ports are found between the shipping routes as shown in Annex 7. If no route is found between any two ports, 999 days are assumed for modelling. Thus, a 154-node shipping network can be formed and modelled. Also, each CR in Annex 1 represents the risk of a territory being affected by climate change investigated by Briguglio (Briguglio, 2010), and CRs of transit ports are assumed as 3. So, a criterion is set up before further investigation: The seaports within a 2-hour circle and 200km travelling distance can be used to represent a traffic flow of the city. The required information is collected from Google map, as shown in Figure 5.1 and 5.2. For example, Tema Harbour is chosen to represent Accra, and Thilawa Port is chosen to represent Yangon. After grouping some sub-urban ports to cities, there are two cities mismatched, Hangzhou and Rabat. By the first criteria, Hangzhou and Rabat can be referenced to Ningbo and Casablanca.

6.5.2. Numerical Settings

The experiments are working on the instances for the number of ports which is like the network size experimented by others before. They are equally separated. The number of ports is set to be 154 (i.e. N = 154). All experiments were performed on a computer equipped with Windows 10, an Intel(R) Core(TM)2 Quad CPU Q9550 @ 2.83GHz 2.83 GHz, and a 8.00GB of RAM, and the program was coded by using Dev-C++ 4.9.9.2.

6.5.3. Special 10-node models

A 10-node model has been designed to validate the experiment result. The heuristic model and a Dijkstra’s shortest path model (Gass and Fu, 2013) implemented by Excel solver are both run to compare the accuracy of the heuristic model and access the possibility of performing experiments that are more complex.

Table 6.1 Travelling time of 10-node model

D\O	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*
2	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*
3	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*
4	*999*	*999*	*999*	*999*	7	2	5	4	*999*	*999*
5	*999*	*999*	*999*	7	*999*	3	15	3	*999*	*999*
6	*999*	*999*	*999*	2	5	*999*	8	2	*999*	*999*
7	*999*	*999*	*999*	5	12	*999*	*999*	2	*999*	*999*
8	*999*	*999*	*999*	4	3	2	11	*999*	*999*	*999*
9	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*
10	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*	*999*

For this special model, 20 numerical runs have been done with different transhipment times, from 0 to 8. Basic service time (S_i^b) is set as 1 day and limit is set as $(N-2)\times 5$. By imparting travelling time and CR for running the model, N-2 possible solutions are calculated in Table 6.2.

Table 6.2 Result of 10-node model with origin port 4 and destination port 5

Transhipment time	Route	Average objective value (days)	Minimum objective value (days)
0	4 -> 5	9	9
1	4 -> 6 -> 5	8	8
2	4 -> 6 -> 8 -> 5	11	11
3	4 -> 8 -> 7 -> 6 -> 5	22	22
4	4 -> 6 -> 8 -> 7 -> 1 -> 5	2012	2012
5	4 -> 6 -> 8 -> 7 -> 1 -> 2 -> 5	3014	3014
6	4 -> 6 -> 8 -> 7 -> 2 -> 3 -> 1 -> 5	4017	4017
7	4 -> 6 -> 8 -> 7 -> 1 -> 2 -> 9 -> 10 -> 5	5020	5020
8	4 -> 6 -> 8 -> 7 -> 2 -> 9 -> 10 -> 1 -> 3 -> 5	6023	6023
Final	4 -> 6 -> 5	8	8

For the Dijkstra's shortest path model, the model is also written in C++ and the result is the same as the model. So, it is proved that the heuristic model can be used to impart a 154-port model. Dijkstra's shortest path model can perform well in Excel solver for a small network, which means less than 30 ports. So, the available paths of a larger scale are found by the optimization technique such as, Ant colony and Bee colony-based optimization (Dhanabal et al., 2018).

6.6. Computation result

There are three parameters for measuring the performance of modelling: (1) The best route between starting port and ending port, and (2) Accumulated minimum times of all the best routes between starting port and ending port with different transhipment times (MinTimes).

The best route between starting port and ending port is used to observe the global climate change impact, each origin-destination pair's best route is found to observe the importance of each port upon different levels of climate change impact. MinTimes is the parameter used to observe the performance of the model, and the minimum of transhipment times is zero and that of maximum is eight. 20 numerical runs have been done for each test and each transhipment time.

We have further conducted two sets of computational experiments. The first set of experiments is to test the performance of the heuristic optimisation programme with the ABC algorithm for assessing the climate resilience of the global shipping network. The integer programming is formulated from equation (6.1) – (6.11). The ABC algorithm is successfully applied to solve the empty container repositioning (ECR) problem (Poo and Yip, 2019) by the integer programming formulation. The difference between the ECR problem and the climate resilience problem is the length of the solution representation. The length of the solution representation is fixed as the N+2 for the ECR problem, and that of this study is from two ports to ten ports. Therefore, the performance is needed to be assessed again, and several amendments on the programme are suggested to improve the performance. Therefore, the neighbourhood operators are tested, and the best values of limit and maximum operation cycle are found to optimise the programme performance. Three pairs of starting ports and ending ports are used for the experiment (Starting port/ Ending port): Benghazi/ Zhanjiang (75/37), Luanda/ Wenzhou (2/34), Copenhagen/ Visakhapatnam (43/59).

6.6.1. Sensitivity Test

Risk of a territory being affected by climate change (CR, I_i) is needed to be assumed before all mathematical calculations. As there is no solid reference for setting up I_i. Different indexes are given to four CR grades in ascending order in five cases. As the convergence test is not done yet, 10,000 iterations are run in this section and combined operator mode is used. Due to the nature of mathematical formation, there are not any extreme changes when S_i^b increases. Therefore, Case C is chosen as it can represent agglomerations with four different CR levels, and difference of MinTimes between different S_i^b is big enough,

Table 6.3 Sensitivity test

	CR (I_i)				**Basic service time (S_i^b)**				
Case	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**5**
A	1	1	1	1	7145 days	8327 days	9450 days	10525 days	11567 days
B	1	1	2	2	7674 days	9338 days	10907 days	12419 days	13884 days
C	1	2	3	4	9111 days	11944 days	14715 days	17318 days	19827 days
D	1	2	4	6	9913 days	13510 days	16918 days	20234 days	23457 days
E	1	3	5	7	10919 days	15347 days	19507 days	23519 days	27486 days

6.6.2. Neighbourhood operator test

By fixing the limit as 760, basic service time as 1 day, and maximum operation cycle as 50,000, three discrete operator modes and a combined mode are tested. The combined mode means choosing randomly between three discrete operator modes. MinTimes of three port pairs are shown in Table 6.4, and it is shown that the combined mode performs the best throughout the four tests for all three port pairs. Therefore, the combined mode is used in the upcoming section.

Table 6.4 Neighbourhood operator test

Starting/ Ending	Random Swap	Reversing a sequence	Random swaps of reversed subsequence	Combined mode
75/37	3867.25 days	2633.5 days	2448.2 days	2089.4 days
2/43	1679.85 days	1173.9 days	887.9 days	809.65 days
43/59	1685.35 days	1180.15 days	888.7 days	817.4 days

6.6.3. Limit test

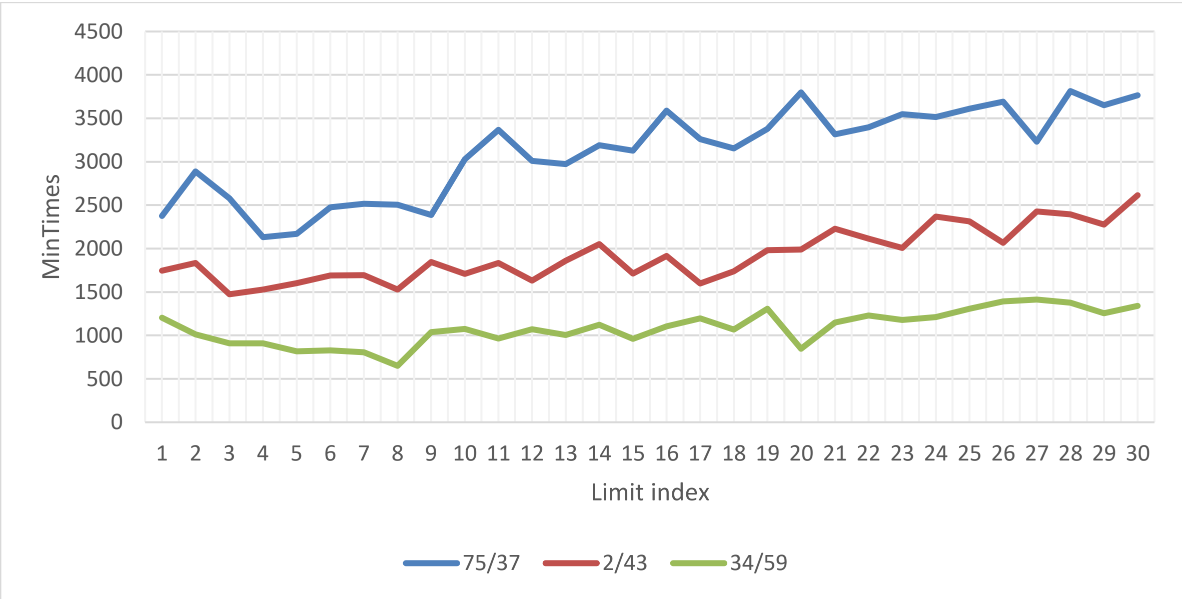

Figure 6.7 Limit test

The same three-port pairs, 75/37, 2/43, and 43/59, are used to assess the best limit value for the model. It is assumed that the limit index is l_i and the limit ($l = (N-2) \times l_i$) is proportional to the potential varying nodes, where N is the number of the port in the network. It is referenced from a vehicle routing study with an artificial bee colony algorithm (Szeto et al., 2011).

Figure 6.7 presents the result of the limit test. The programme can find better results, which mean a smaller MinTimes, when the l_i is set between 4 and 8. So, l_i is set as 5 upon the upcoming experiments, also basic service time as 1 day and the limit is 760. As the limit is proportional to the number of running cycles, an improvement is needed to adjust the limit of the experiments with fewer transmission times. Then, a new index, saturation rate (SR), is needed for amending the limit. Without shuffling the route, the number of possible solutions equals the factorial of transmission times. For example, 24 (4!) solutions are found if there are four transmission times, and it is much lower than 760, which is the default limit. SR is used to multiply the corresponding factorial to obtain a new limit to enhance the route searching performance. For example, if there are four transmissions and SR is 80%, the new limit is 19 $(80\% \times 4!)$. The lower value between the new limit and default limit is used for running the model. Then, the optimal value of SR is examined in Figure 6.8.

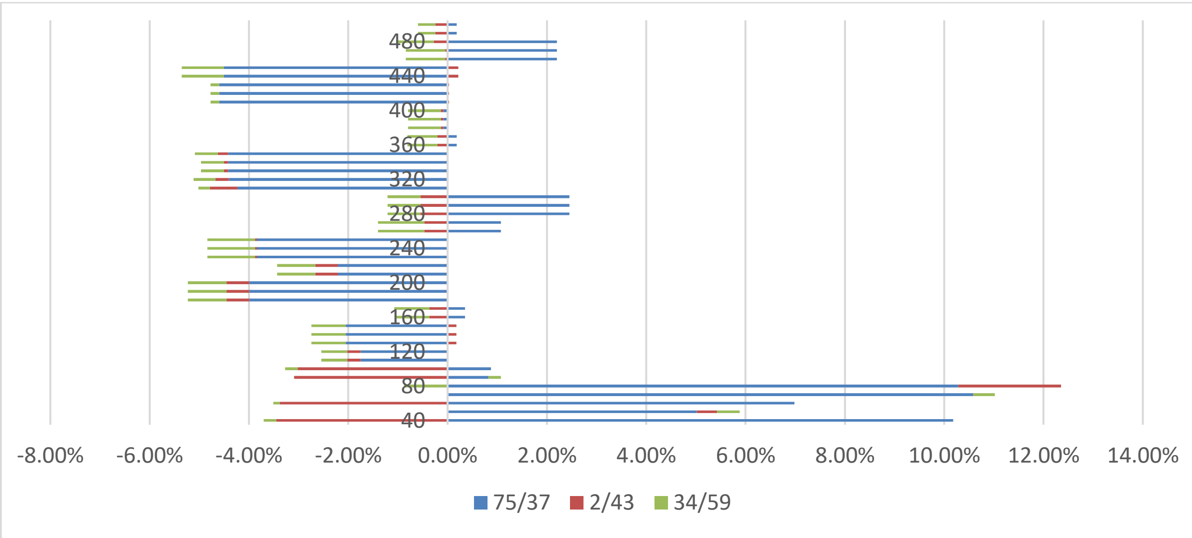

Figure 6.8 Saturation rate test

If the saturation rate is set less than 100%, the new results are unstable and frequently larger than the default result. So, the testing range of the saturation rate is from 40% to 500%. The saturation is set to 220% for the upcoming experiments as there is possible reduction between 90% and 270%, and the reduction range of experiment is from 0.46% to 2.2%.

6.6.4. Convergence Test

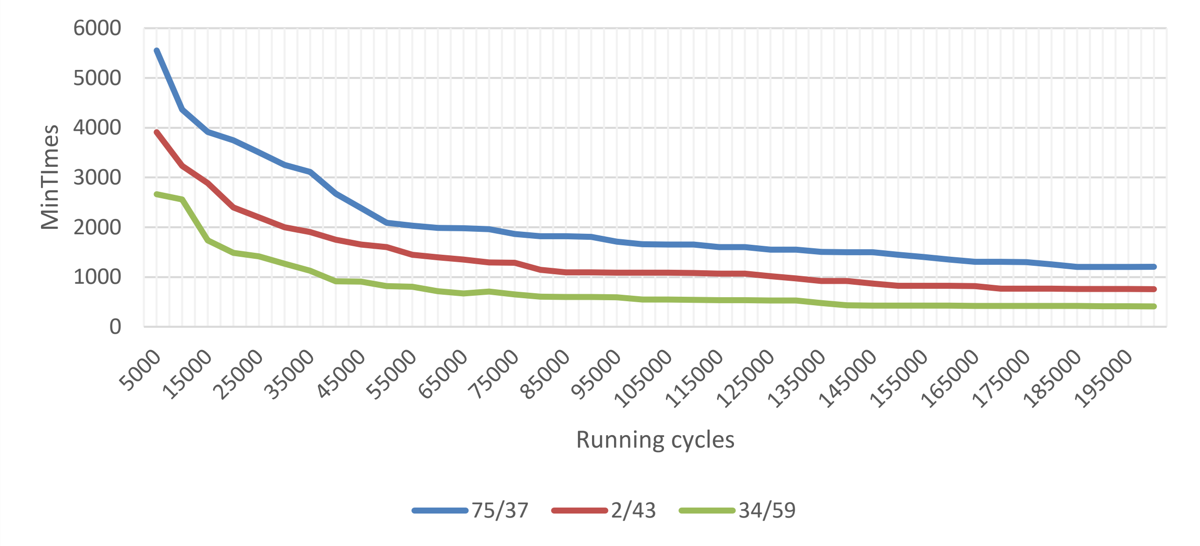

Figure 6.9 Convergence Test

The objective value of the first period is used as the parameter to measure the performance of the model and to find out the convergence point. By increasing the number of iterations, the accumulated net profit increases with the decreasing rate and converges after the iteration of 80,000. Therefore, we can conclude that 100,000 iterations can be used as the basic parameter to undertake the following experiments.

6.7. Climate resilience assessment

Different basic service days are assigned to run the model to forecast the shipping routing in the future with more extreme weather and port disruption days. Changes on route selection by the increase of service days can imply changes in the nature of the global shipping network and the importance of each port. Therefore, the three port pairs are used to implement the climate change impact assessment by assigning one to five basic service days. The best routes with different basic service days and port pairs are shown in Table 6.5. The route from Benghazi (75) to Zhanjiang (37) is going across Krishnapatnam (140), Tanjung Pelepas (148), and Hong Kong (38). The route from Luanda (2) to Denmark (34) is going across Cape Town (101), London (112), and Hamburg (49). The route from Wenzhou (34) to Visakhapatnam (59) varies if basic service time increases. If basic service time is one day, it goes across Hong Kong (38), Cape Town (148), and Colombo (137). If basic service time is more than one day, it just passes through Hong Kong (38), and Colombo (137).

Table 6.5 Climate change impact assessment on route selection

Basic service time	Route for 75/37	Route for 2/43	Route for 34/59

1 day	75 -> 140 -> 148 -> 38 -> 37	2 -> 101 -> 112 -> 49 -> 43	34 -> 38 -> 148 -> 137 -> 59
2 days	75 -> 140 -> 148 -> 38 -> 37	2 -> 101 -> 112 -> 49 -> 43	34 -> 38 -> 137 -> 59
3 days	75 -> 140 -> 148 -> 38 -> 37	2 -> 101 -> 112 -> 49 -> 43	34 -> 38 -> 137 -> 59
4 days	75 -> 140 -> 148 -> 38 -> 37	2 -> 101 -> 112 -> 49 -> 43	34 -> 38 -> 137 -> 59
5 days	75 -> 140 -> 148 -> 38 -> 37	2 -> 101 -> 112 -> 49 -> 43	34 -> 38 -> 137 -> 59

It can prove that the model can observe the route changes and the service time affects the shipping route selection. But it is necessary to examine all port pairs to observe the changes in the whole shipping network. Therefore, a case study on top 20 agglomerations and a whole network assessment are done separately. As top 20 agglomerations are the key hubs in the global shipping network, they can be used to observe the global shipping route changes. Furthermore, a whole shipping network assessment is also necessary as the importance of each agglomeration needs to be assessed. The mechanism of the assessments is assigning three basic service time (S_i^b), one day, three days, and five days. One day is assumed as the present situation and the other cases represent the near future and the long future situation.

6.7.1. Top 20 assessment

The top 20 port cities are assigned as five regions as Table 5.3. Then, the changes of 190 origin-destination (OD) pairs between them are recorded, and the OD pairs between the same region are exempted. First, S_i^b is assumed as one day and runs the programme. Then, S_i^b is assumed as three days and five days and the positive and negative changes are recorded in Table 6.6 and 6.7. Then, Hong Kong (38), Rotterdam (82), Singapore (99), and London (112) become more important to the global shipping network as they are shown in Table 6.8 more than 3 times. On the other hand, Shenzhen (28), Qingdao (30), Shanghai (31), Panama City (86), Busan (93), and New York (120) are listed in Table 6.7 more than 3 times, which means a reduction on influence.

Table 6.6 Summary of top 20 agglomerations having lower influence on global shipping network by climate change

	From				
	North America	South America	Europe	West Asia	East Asia

	North America	N/A	Shenzhen (28), Barranquilla (39), Busan (93), Philadelphia (121)	No change	New York (120)	Melbourne (6) Shenzhen (28) Shanghai (31) Guayaquil (45) Los Angeles (117), San Diego (124)
	South America	Santo Domingo (44), Panama City (86), Miami (118), New Orleans (119)	N/A	Panama City (86)	New York (120)	Qingdao (30), Shanghai (31), Hong Kong (38) Tokyo (72), Kuala Lumpur (77), Panama City (86)
To	Europe	London (112) Miami (118) New York (120)	No change	N/A	No change	Shenzhen (28), Kuala Lumpur (108)
	West Asia	No change	No change	Rotterdam (82)	N/A	Guangzhou (27), Wenzhou (34), Mumbai (57), Busan (93)
	East Asia	Shenzhen (28), Qingdao (30), Shanghai (31), Hamburg (49), Busan (93), Inchon (95), Miami (118)	Shenzhen (28), Ningbo (29), Qingdao (30), Hamburg (40), Busan (93)	Rio de Janeiro (12), Shenzhen (28), Shanghai (31), Hamburg (49), Busan (93)	Shenzhen (28), Bangkok (105)	N/A

Table 6.7 Summary of top 20 agglomerations having higher influence on global shipping network by climate change

		From				
		North America	South America	Europe	West Asia	East Asia
	North America	N/A	Singapore (99)	No change	London (112)	Brisbane (5), Tokyo (72), Auckland (83), Lisbon (90), Busan (93)
To	South America	No change	N/A	London (112)	Singapore (99), London (112)	Santos (12), Auckland (83), Los Angeles (117)
	Europe	Lisbon (90)	No change	N/A	London (112)	Jeddah (97), Singapore (99)
	West Asia	No change	Singapore (99)	No change	N/A	Melbourne (6), Hong Kong (38), Singapore (99)

East Asia	Tokyo (72), Rotterdam (82), San Francisco (125), San Jose (126) Seattle (127)	Hong Kong (38), Rotterdam (82), Singapore (99), Miami (118)	Jeddah (97), Singapore (99)	Hong Kong (38), Singapore (99)	N/A

6.7.2. Global shipping network assessment

11,935 OD pairs between 154 port cities are assessed, and their routes are all evaluated by the program. The highest 10 positive and negative changes from the present ($S_i^b = 1$) to the near future ($S_i^b = 3$) and long future ($S_i^b = 5$) are recorded to show the changes among all seaports. Then, the changes of total transhipments are also counted to observe the changing natures of routing. Kuala Lumpur (77) is ranked number 1 on both changes. Then, Shenzhen (28), Busan (93), Santos (12), Dubai (110), Shanghai (31), Barranquilla (39), Hamburg (49), and Miami (18) are listed twice in the table. Finally, Ningbo (29) and Panama City (86) are on the table once. For the higher influence side, Singapore (99) is ranked number 1 twice, and Tokyo (72) and Barcelona (103) are both in the top 3 twice. Then, Lisbon (90), Hong Kong (38), Yangon (80), Jeddah (97), and Naples (66) are ranked twice in Table 6.9 while Montreal (23), Vancouver (24), Athens (51), and Tel Aviv (65) are only ranked once. Furthermore, the total number of transhipments on each agglomeration is counted by the three cases again, and it drops as -14.22% in the near future and -19.12% in the long future.

Table 6.8 Rank of agglomerations having a lower influence on global shipping network by climate change

	Changes in the near future			**Changes in the long future**		
Rank	**ID**	**Agglomerations**	**Changes**	**ID**	**Agglomerations**	**Changes**
1	77	Kuala Lumpur	-530	77	Kuala Lumpur	-686
2	28	Shenzhen	-354	93	Busan	-420
3	93	Busan	-292	12	Santos	-379
4	12	Santos	-230	28	Shenzhen	-318
5	110	Dubai	-209	49	Hamburg	-310
6	31	Shanghai	-204	110	Dubai	-277
7	39	Barranquilla	-200	31	Shanghai	-258
8	49	Hamburg	-190	86	Panama City	-232
9	29	Ningbo	-184	118	Miami	-229
10	118	Miami	-184	39	Barranquilla	-214

Table 6.9 Rank of agglomerations having higher influence on global shipping network by climate change

	Changes in the near future			Changes in the long future		
Rank	**ID**	**Agglomerations**	**Changes**	**ID**	**Agglomerations**	**Changes**
1	99	Singapore	378	99	Singapore	739
2	72	Tokyo	185	103	Barcelona	257
3	103	Barcelona	138	72	Tokyo	225
4	90	Lisbon	63	97	Jeddah	112
5	38	Hong Kong	56	90	Lisbon	93
6	80	Yangon	50	66	Naples	54
7	97	Jeddah	46	80	Yangon	28
8	66	Naples	15	51	Athens	25
9	23	Montreal	5	65	Tel Aviv	19
10	24	Vancouver	4	38	Hong Kong	11

6.8. Discussion

This chapter presents a new method for assessing the climate risks of global shipping network, by integrating climate risk indicators, centrality assessment, and shipping routing model. Also, it shows the possible changes in shipping routing. Except for reducing local CR, some other methods can be used. As more port disruption due to climate change likely takes place more frequently and it is inevitable, it is necessary to provide more routes as the total number of transhipments is decreased. The new routes can be added to bear the risks of port disruption in any location, and it can be known as decentralisation as mentioned in Section 5.4.

CR used in this section can be known as a reference for climate exposure. However, it is not enough to assess the climate resilience for seaports as climate sensitivity and adaptive capacity are not assessed. Also, CR just includes climate threats from sea-level rise and storming. The climate exposure is not fully assessed. A more comprehensive and worldwide CRI framework is necessary for an in-depth global shipping network evaluation.

Furthermore, the model constructed is possible to be enhanced as a MOO model by modifying adding more components to the objective function, as known as Equation 6.2. It is possible to encounter some more factors, such as traffic flow or ship capacity, for this shipping model.

Chapter 7 Conclusion

The conclusion starts by recalling the three research objectives, identifying climate risk and resilience indexes to seaport and airport planning, evaluating the risk of climate change and adaptation necessity in the UK seaports and airports, and constructing a routing model for assessing the climate resilience of global transportation network modelling. The success in the objectives of the previous chapters is discussed. Then, the challenges and future research directions are discussed afterwards.

Identifying climate risk and resilience indexes for seaports and airports, and evaluating the risk of climate change and adaptation necessity in the UK seaports and airports are the first and second objectives, and they have been presented in Chapter 3 to 4. CCRI framework and CRI framework have been designed for assessing the risk and resilience, respectively. CCRI framework is for assessing the monthly climate risks to alert seaports authorities and airport authorities. Therefore, they can provide suitable adaptation measures for the corresponding period. CRI framework is for comparing the climate resilience of seaports and airports on the national scale. By implementing CCRI and CRI frameworks, seaports and airports have been evaluated with climate risk and resilience perspectives. And, the results can be used as a reference on adaptation necessity. The first objective and second objective has been successfully responded.

The most challenging part of these objectives is collecting regional data. The first version of the CRI framework requires more data input which cannot be found, such as the frequency and intensity of fog events, and from the seaport and airport operators. However, it is impossible to generate some usable findings as it may be a part of the trade secret. Therefore, FER plays a more critical role in the study as it can be used to generate some useful findings to compare seaports and airports. Apart from the lack of data, the scope of data is also a barrier for data collection. The extreme events data is not regional, which is not suitable for comparison.

For the future perspective, many projects can be stood on the base of this thesis. Firstly, an international comparison on seaports and airports by CCRI framework and CRI framework can be made. Therefore, the strategic resilience seaport or airport groups can be expanded. On the other hand, an analysis of the influences by different climate seaports and airports have been assessed. It can be used on utilising climate adaptation strategies. MOO, which has been urgently called in for climate change, can be used to assist authorities on allocating resources for adaptation measures by combining knowledges different chapters and integrating some more factors to assess the importance of different shipping routes.

Constructing a routing model for assessing the climate resilience of global transportation network modelling is the final objective. By the centrality assessment in Chapter 5 and the global shipping routing model in Chapter 6, the climate resilience of the global shipping network has been assessed.

The most challenging part of these objectives is finding the global reference to port disruption impacts. Therefore, the reference from Pascal Briguglio (2010) has been chosen for further analysis. However, it is not as extensive and specialised for transportation infrastructure as CCRI framework and CRI framework.

For the future perspective, it is possible to utilise the two studies by a more comprehensive CR dataset by enquiring more data input from the foreign governmental bodies, shipping authorities, academics, and shipping companies. Therefore, a more comprehensive finding can be generated. Furthermore, the international frameworks by CCRI and CRI can play a more critical role, and provide a novel CR dataset for assessment. Also, such a routing network can be implemented to different scales. For example, the impact on shipping companies can be assessed by constructing the networks by two companies' data.

During the write-up period, Australian fires and Venice flooding become headlines in many newspapers for more than a day. Therefore, climate change is a part of our daily life. However, the response rate to the nationwide questionnaire is not high. Although it comes with different reasons, it can still answer that the alerts from the seaports and airports on climate change are not active enough. Here is an anonymous response from a seaport professional,

"Whilst I'm a stakeholder in leaving a lovely world to our children's children - I'm not convinced this climate change is to do with fossil fuel burning - looking back in history are we not on a pattern?

The ice age happened and was nothing to do with sea or airports

Just saying"

No man is an island. It takes more efforts to warn people from different sectors, including operators and public, to work together on climate change mitigation but also adaptation. This thesis is not the end of the CCRI framework and CRI framework. They can be implemented into adaptation decision making and resource allocation. Also, it is possible to implement into the network modelling to visualise the changes in global aviation and shipping networks in the coming years. Global climate is projected to change continuously over this century and beyond. Climate change adaptation plays a more critical role as climate change mitigation has been. Both adaptation and mitigation require more cooperation and alert to protect the world from climate vulnerabilities.

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Annex 1 List of Climate change risk indicators and Climate resilience indicators

Index number	1	**Unit**	mm
Indicator	Precipitation UB		
Description	Total precipitation amount over the calendar month (Upper bound)		
Data source	The data produced by the UK Met Office providing information on plausible changes in 21st century climate for the UK helping to inform on adaptation to a changing climate. Past (observed) climate and future climate scenario projections data that were produced as part of the UK climate projections 2009 (UKCP09) service. Criterion percentile margins of upper bound are 60, 70 80 90, and 95. And, criterion percentile margins of lower bound are 40, 30, 20, 10, and 5. Historical resolution is 5 km x 5 km, and forecasting resolution is 12 km x 12 km.		
Example value	Felixstowe in June: 53.49 mm Glasgow airport in December: 147.72 mm		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	2	**Unit**	N/A
Indicator	Days of rain >= 10 mm UB		
Description	Count of days when the daily precipitation is higher than 10 mm (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 1.19 Glasgow airport in December: 3.99		
Monthly data	Yes	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	3	**Unit**	knots
Indicator	Mean wind speed UB		
Description	Average of hourly mean wind speed at a height of 10 m above ground level over the month (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 12.35 knots Glasgow airport in December: 11.59 knots		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	4	**Unit**	hPa
Indicator	Mean sea level pressure LB		
Description	Average of hourly (or 3-hourly) mean sea level pressure over the month (Lower bound)		

Data source	Same as Index 1		
Example value	Felixstowe in June: 1016.45 hPa Glasgow airport in December: 1010.25 hPa		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	5	**Unit**	hPa
Indicator	Mean vapour pressure LB		
Description	Average of hourly (or 3-hourly) vapour pressure over the month (Lower bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 13.05 hPa Glasgow airport in December: 7.35 hPa		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	6	**Unit**	m
Indicator	Skew surges records		
Description	Average of Top 10 skew surges records		
Data source	British Oceanographic Data Centre is a national facility for collecting and releasing data about the marine environment for the UK and it is a part of the National Oceanography Centre (NOC). Highest sea level records and skew surge are listed.		
Example value	Dover: 1.24 m Leith 0.82 m		
Monthly data	No	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	7	**Unit**	N/A
Indicator	Days of thunder		
Description	Days of thunder in a month		
Data source	Same as Index 1		
Example value	Felixstowe in June: > 14 days Glasgow airport in December: 4 to 6 days		
Monthly data	No	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	8	**Unit**	m
Indicator	Sea level records		
Description	Average of Top 10 sea level records		
Data source	Same as Index 6		

Example value	Dover: 4.14 m Leith 3.51 m		
Monthly data	No	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	9	**Unit**	ºC
Indicator	Maximum temperature UB		
Description	Average of daily maximum air temperature over the calendar month (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 18.31 ºC Glasgow airport in December: 6.75 ºC		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	10	**Unit**	%
Indicator	Relative humidity LB		
Description	Average of hourly (or 3-hourly) relative humidity over the month (Lower bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 80.52 % Glasgow airport in December: 86.82 %		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	11	**Unit**	%
Indicator	Relative humidity LB		
Description	Average of hourly (or 3-hourly) relative humidity over the month (Lower bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 80.52% Glasgow airport in December: 86.82%		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	12	**Unit**	%
Indicator	Cloud cover LB		
Description	Average of hourly (or 3-hourly) cloud cover over the month (Lower bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 64.49%		

	Glasgow airport in December: 73.22%		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	13	**Unit**	ºC
Indicator	Minimum temperature LB		
Description	Average of daily minimum air temperature over the calendar month (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 10.81 ºC Glasgow airport in December: 1.37 ºC		
Monthly data	Yes	**Forecasting data**	Yes
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	14	**Unit**	N/A
Indicator	Days of air frost UB		
Description	Count of days when the minimum air temperature is below 0 ºC (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 0.02 Glasgow airport in December: 10.61		
Monthly data	Yes	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	15	**Unit**	N/A
Indicator	Days of ground frost UB		
Description	Count of days when the grass minimum temperature is below 0 ºC (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 0.43 Glasgow airport in December: 17.53		
Monthly data	Yes	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	16	**Unit**	N/A
Indicator	Days of sleet or snow falling UB		
Description	Count of days with sleet or snow falling (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 0.01		

	Glasgow airport in December: 3.59		
Monthly data	Yes	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	17	**Unit**	N/A
Indicator	Days of snow lying UB		
Description	Count of days with greater than 50% of the ground covered by snow at 0900 UTC (Upper bound)		
Data source	Same as Index 1		
Example value	Felixstowe in June: 0 Glasgow airport in December: 2.25		
Monthly data	Yes	**Forecasting data**	No
CCRI	Yes	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	18	**Unit**	N/A
Indicator	NumberSAC		
Description	Number of Special Areas of Conservation in port county		
Data source	Joint Nature Conservation Committee (JNCC), which is the public body that advises the UK Government and devolved administrations on UK-wide and international nature conservation.		
Example value	Suffolk: 0 West Wales and The Valleys: 74		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	19	**Unit**	N/A
Indicator	AQDailyIndex		
Description	Count of days with Air Quality Daily index > 5		
Data source	Defra provides the Daily Air Quality Index (DAQI) about levels of air pollution and provides recommended actions and health advice. The index is numbered 1-10 and divided into four bands, low (1) to very high (10), to provide detail about air pollution levels in a simple way, like the sun index or pollen index.		
Example value	Eastern: 26 Glasgow Urban Area: 2		
Monthly data	Yes	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	20	**Unit**	N/A
Indicator	Brownfield ratio		
Description	Brownfield ratio higher than 0.5%		

Data source	The National Housing Federation (NHF), which is a trade or industry body representing providers of housing, much of it termed affordable housing in England. In the United Kingdom, the term 'brownfield' has a colloquial meaning roughly equivalent to the American usage described above, i.e. vacant or derelict land or property, usually industrial in nature. This interactive map is designed to make it easier to locate available brownfield sites in England. It brings together, for the first time, comprehensive information on all brownfield sites in the country. In terms of British Town and Country Planning, however, the meaning of 'brownfield' is more complex, and is often conflated with the technical term 'previously developed land' (PDL). PDL was originally defined in planning policy for housing development in England and Wales, and it was carefully distinguished in such policy from 'brownfield', which was undefined but considered to be different. The definition from the 2012 National Planning Policy Guidance, which only applies to England, uses the terms 'brownfield' and 'previously developed land' interchangeably: "Land which is or was occupied by a permanent structure, including the curtilage of the developed land (although it should not be assumed that the whole of the curtilage should be developed) and any associated fixed surface infrastructure. This excludes: • land that is or has been occupied by agricultural or forestry buildings; • land that has been developed for minerals extraction (mining) or waste disposal by landfill purposes where provision for restoration has been made through development control procedures; • land in built-up areas such as private residential gardens, parks, recreation grounds and allotments; and • land that was previously-developed but where the remains of the permanent structure or fixed surface structure have blended into the landscape in the process of time."		
Example value	Suffolk Coastal: 0.06% Manchester: 1.3%		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	21	**Unit**	N/A
Indicator	ShelterAfford		
Description	The shelter afforded from wind, sea, and swell, refers to the area where normal port operations are conducted, usually the wharf area. Shelter afforded the anchorage area is given for ports where cargo is handled by lighters.		

Data source	The Twenty-Seventh Edition of Pub 150, World Port Index, cancels the previous edition of Pub 150. This publication gives the location, characteristics, known facilities, and available services of a great many ports and shipping facilities and oil terminals throughout the world. The selection of these places is based on criteria established by this Agency. They are not random choices. The applicable chart and Sailing Directions are given for each place listed. The edition contains information available to the National Geospatial-Intelligence Agency up to 31 August 2019, including Notice to Mariners No. 35 of 2019.		
Example value	Felixstowe: Fair Liverpool: Excellent		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	22	**Unit**	N/A
Indicator	EntranceRestrictions		
Description	Types of natural factors restricting the entrance of vessels, “Tide”, “Swell”, “Ice”, “Other”		
Data source	Same as Index 21		
Example value	Felixstowe: 3 Liverpool: 3		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	23	**Unit**	Binary
Indicator	OverheadLimits		
Description	Presence or absence of overhead limitations, such as bridge and overhead power cables.		
Data source	Same as Index 21		
Example value	Dundee: Yes Liverpool: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	24	**Unit**	N/A
Indicator	ChannelDepth		
Description	The controlling depth of the principal or deepest channel at chart datum. Depth information is generalized into 5-foot units, with the equivalents in meters, for the main channel, the main anchorage, and the principal cargo pier and/or oil terminal. Depths refer to		

	chart datum. Depths are given in increments of 5 feet (1.5 meters) to lessen the number of changes when a small change in depth occurs. A depth of 31 feet (9.5 meters) would use letter "K," a depth of 36 feet (11.0 meters) would use "J," etc. The letter "K" means a least depth of 31 feet (9.5 meters) or greater, but not as great as 36 feet (11.0 meters).		
Data source	Same as Index 21		
Example value	Felixstowe: G (46 – 51 feet) Liverpool: M (21 – 25 feet)		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	25	**Unit**	N/A
Indicator	PierDepth		
Description	The greatest depth at chart datum alongside the respective wharf/pier. Depth information is generalized into 5-foot units, with the equivalents in meters, for the main channel, the main anchorage, and the principal cargo pier and/or oil terminal. Depths refer to chart datum. Depths are given in increments of 5 feet (1.5 meters) to lessen the number of changes when a small change in depth occurs. A depth of 31 feet (9.5 meters) would use letter "K," a depth of 36 feet (11.0 meters) would use "J," etc. The letter "K" means a least depth of 31 feet (9.5 meters) or greater, but not as great as 36 feet (11.0 meters).		
Data source	Same as Index 21		
Example value	Felixstowe: J (46 – 40 feet) Liverpool: M (21 – 25 feet)		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	26	**Unit**	Meters
Indicator	TideRange		
Description	Mean tide range at the port		
Data source	Same as Index 21		
Example value	Felixstowe: 2 meters Liverpool: 6 meters		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	27	**Unit**	€ million
Indicator	GDP		
Description	Gross domestic product		

Data source	Eurostat (European Statistical Office) is responsible are to provide statistical information to the institutions of the European Union (EU) and to promote the harmonisation of statistical methods across its member states and candidates for accession as well as EFTA countries. The organisations in the different countries that cooperate with Eurostat are summarised under the concept of the European Statistical System. GDP (gross domestic product) is an indicator for a nation´s economic situation. It reflects the total value of all goods and services produced less the value of goods and services used for intermediate consumption in their production. Expressing GDP in PPS (purchasing power standards) eliminates differences in price levels between countries, and calculations on a per head basis allows for the comparison of economies significantly different in absolute size.		
Example value	East Anglia: €80,329 million South Western Scotland: €72,754 million		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	28	**Unit**	£
Indicator	GVA		
Description	Gross Value Added per head per month		
Data source	The Office for National Statistics, which is the executive office of the UK Statistics Authority, a non-ministerial department which reports directly to the UK Parliament.		
Example value	Suffolk: £22,811 Inverclyde, East Renfrewshire, and Renfrewshire: £19,082		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	29	**Unit**	%
Indicator	SeaportMarketShare		
Description	Seaport market share in the UK		
Data source	The Department for Transport (DfT) is the government department responsible for the English transport network and a limited number of transport matters in Scotland, Wales and Northern Ireland that have not been devolved.		
Example value	Felixstowe: 5.99% Liverpool: 6.91%		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	30	**Unit**	%

Indicator	SeaportDirectEmployment		
Description	The regional breakdown of direct employment and the compensation of employees directly supported by the Maritime Sector		
Data source	Maritime UK, which is the promotional body for the UK maritime sector. The UK's maritime sector comprises shipping, ports, marine and maritime business services.		
Example value	Felixstowe: 7.1% Liverpool: 10%		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	31	**Unit**	N/A
Indicator	SoVIflood		
Description	Socio-spatial vulnerability index on flooding		
Data source	Climate Just is an information tool designed to help with the delivery of equitable responses to climate change at the local level. Its focus is to assist the development of socially just responses to the impacts of extreme events, such as flooding and heatwaves, as well as supporting wider climate change adaptation. It also includes issues related to fuel poverty and carbon emissions. There are seven levels, extremely high, relatively high, average, relatively low, extremely low, and slight.		
Example value	Suffolk Coastal: 5 Manchester: 7		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	32	**Unit**	N/A
Indicator	SoVIflood		
Description	Socio-spatial vulnerability index on flooding		
Data source	Same as Index 31		
Example value	Suffolk Coastal: 5 Manchester: 7		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	33	**Unit**	£
Indicator	HousePrice		
Description	UK House Price Index. It uses house sales data from HM Land Registry, Registers of Scotland, and Land and Property Services Northern Ireland and is calculated by the Office for National Statistics. The index applies a statistical method, called a hedonic regression model, to the various sources of data on property price		

	and attributes to produce estimates of the change in house prices each period. The index is published monthly, with Northern Ireland figures updated quarterly.		
Data source	Her Majesty's Land Registry, which is a non-ministerial department of the Government of the United Kingdom, created in 1862 to register the ownership of land and property in England and Wales. It reports to the Department for Business, Energy and Industrial Strategy.		
Example value	Suffolk Coastal: £290115 Manchester: £184661		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	34	**Unit**	%
Indicator	CongestionIndex		
Description	TomTom Traffic Index, historic road congestion levels in cities.		
Data source	TomTom N.V. is a Dutch multinational developer & creator of location technology and consumer electronics. Founded in 1991 and headquartered in Amsterdam, TomTom released its first generation of satellite navigation devices to market in 2004.		
Example value	Liverpool: 27% London: 37%		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	35	**Unit**	N/A
Indicator	SeaportRailConnection		
Description	Presence of direct rail connections, over 1,000 tons “Large”, 200 – 1000 tons “Medium”, up to 200 tons “Small”, “No”.		
Data source	Same as Index 21		
Example value	Felixstowe: Small London: Medium		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	36	**Unit**	N/A
Indicator	HarborSize		
Description	The classification of harbor size is based on several applicable factors, including area, facilities, and wharf space. It is not based on area alone or on any other single factor. Presence of direct rail connections, “Large”, “Medium”, “Small”, “Very Small”.		
Data source	Same as Index 21		
Example value	Felixstowe: Large		

	London: Medium		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	37	**Unit**	N/A
Indicator	SeaportPassengerTraffic		
Description	Total passenger traffic in a year		
Data source	Same as Index 29		
Example value	Felixstowe: 0 Liverpool: 660		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	38	**Unit**	tons
Indicator	SeaportFreightTraffic		
Description	Total freight traffic in a year		
Data source	Same as Index 29		
Example value	Felixstowe: 28268 tons Liverpool: 32613 tons		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	39	**Unit**	N/A
Indicator	NumberBerth		
Description	Number of berths at the port		
Data source	The UK PORTS DIRECTORY is created and maintained by Compass Handbooks Ltd who have over 30 years' experience of working with a variety of clients in the seaport, airport, tourism, industrial and NGO sectors to deliver a range of quality, authoritative media.		
Example value	Felixstowe: 9 Liverpool: 50		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	40	**Unit**	N/A
Indicator	NumberCraneType		
Description	Number of crane types at the port. Three types are defined, "Floating", "Mobile", "Fixed".		
Data source	Same as Index 21		
Example value	Felixstowe: 3		

	Liverpool: 1		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	41	**Unit**	N/A
Indicator	NumberLiftType		
Description	Number of lift types at the port. Four types are defined, “100 tons plus”, “50 – 100 tons”, “25 – 49 tons”, “0 – 24 tons”.		
Data source	Same as Index 21		
Example value	Felixstowe: 4 Liverpool: 2		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	No

Index number	42	**Unit**	Binary
Indicator	MasterPlan		
Description	Do seaport/airport master plans consider resilience?		
Data source	Climate change adaptation reports under the Climate Change Act, reporting to Environment Agency.		
Example value	Felixstowe: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	43	**Unit**	Binary
Indicator	LocalPlan		
Description	Do State and Local Adaptations Plans consider resilience?		
Data source	Same as Index 21		
Example value	Felixstowe: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	44	**Unit**	Binary
Indicator	SustainabilityPlan		
Description	Does the seaport have sustainability plan?		
Data source	Same as Index 21		
Example value	Felixstowe: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes

Seaport data	Yes	**Airport data**	Yes

Index number	45	**Unit**	Binary
Indicator	%changePassengerFreight		
Description	Positive annual percentage change in passenger or freight		
Data source	Same as Index 37.		
Example value	Felixstowe: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	46	**Unit**	Binary
Indicator	%changeMarketshare		
Description	Positive annual percentage change in market share		
Data source	Same as Index 37.		
Example value	Felixstowe: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	Yes	**Airport data**	Yes

Index number	47	**Unit**	%
Indicator	AirportMarketShare		
Description	Airport market share in the UK		
Data source	The Civil Aviation Authority is the statutory corporation which oversees and regulates all aspects of civil aviation in the United Kingdom. Its areas of responsibility include: Supervising the issuing of pilots' licences, testing of equipment, calibrating of navaids, and many other inspections.		
Example value	Heathrow: 27.4% Manchester: 9.7%		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	48	**Unit**	%
Indicator	AirportDirectEmployment		
Description	The regional breakdown of direct employment and the compensation of employees directly supported by the aviation sector		
Data source	Beyond the horizon the future of UK aviation by HM government		
Example value	Heathrow: 22% Manchester: 12%		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes

Seaport data	No	**Airport data**	Yes

Index number	49	**Unit**	min
Indicator	Punctuality Statistics		
Description	Average delay of flights		
Data source	Same as Index 47		
Example value	Heathrow: 12.95 mins Manchester: 16.27 mins		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	50	Unit	N/A
Indicator	AirportRailConnection		
Description	Presence of direct rail connections		
Data source	World Airport Codes provides info for almost every airport in the world, including airport codes, abbreviations, runway lengths and other airport details.		
Example value	Heathrow: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	51	Unit	N/A
Indicator	RunwayLength		
Description	The longest runway length in the airport. Three types are defined, ">3048m", "2438 – 3048 m", and "< 2438 m".		
Data source	Same as Index 50		
Example value	Heathrow: >3048m Manchester: >3048m		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	52	**Unit**	N/A
Indicator	AirportPassengerTraffic		
Description	Total passenger traffic in a year		
Data source	Same as Index 47		
Example value	Heathrow: 80100311 Manchester: 28254970		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	53	**Unit**	tons
Indicator	AirportFreightTraffic		
Description	Total freight traffic in a year		
Data source	Same as Index 47		
Example value	Heathrow: 1699663 tons Manchester: 114131 tons		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	54	Unit	N/A
Indicator	NumberRunway		
Description	Number of runways. Two types are defined, ">2", and "1".		
Data source	Same as Index 50		
Example value	Heathrow: >2 Manchester: >2		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Y.es

Index number	55	Unit	N/A
Indicator	NumberTerminal		
Description	Number of terminals. Two types are defined, ">2", and "1".		
Data source	Same as Index 50		
Example value	Heathrow: >2 Manchester: >2		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	56	**Unit**	Binary
Indicator	%changeAirportPassengerFreight		
Description	Positive annual percentage change in passenger or freight		
Data source	Same as Index 47		
Example value	Heathrow: Yes Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Index number	57	**Unit**	Binary
Indicator	%changeAirportMarketshare		
Description	Positive annual percentage change in market share		
Data source	Same as Index 47		
Example value	Heathrow: Yes		

	Manchester: Yes		
Monthly data	No	**Forecasting data**	No
CCRI	No	**CRI**	Yes
Seaport data	No	**Airport data**	Yes

Annex 2 CRI framework for seaports

Category	Sub-category	Sub-sub-category	Sub-sub-sub-category	No.	Description	Indicator	Units	Types	Level	Data Source
Exposure	Damaging cyclone	Precipitation		1	Total precipitation amount over the calendar month, season, or year. (Upper bound) 1	**Precipitation UB 1**	mm	Qualitatve	5	Met Office
				2	Count of days with >= 10mm precipitation (Upper bound) 1	**Days of rain >= 10 mm UB 2**	Days	Qualitatve	5	Met Office
		Wind		3	Average of hourly mean wind speed at a height of 10 m above ground level (Upper bound)	**Mean wind speed UB**	knots	Qualitatve	5	Met Office
		Pressure		4	Average of hourly mean sea level pressure (Lower bound)	**Mean sea level pressure LB**	kts	Qualitatve	5	Met Office
				5	Average of hourly vapour pressure (Lower bound)	**Mean vapour pressure LB**	kts	Qualitatve	5	Met Office
		Storm Surge		6	Top 10 skew surges records 1	**Skew surges records 1**	m	Qualitatve	5	BODC
		Lightning		7	Days of thunder in a month	**Days of thunder**	Days	Qualitatve	7	Met Office
	Sea-level rise	Sea level		8	Top 10 sea level records	**Sea level records**	m	Qualitatve	5	BODC
		Storm Surge		6	Top 10 skew surges records 2	**Skew surges records 2**	m	Qualitatve	5	BODC
	Warming trend/ Extreme temperature/ Drought	Temperature		9	Average of daily maximum air temperature (Upper bound)	**Maximum temperature UB**	°C	Qualitatve	5	Met Office
		Relative humidity		10	Average of hourly relative humidity (Lower bound)	**Relative humidity LB**	%	Qualitatve	5	Met Office
		Precipitation		11	Total precipitation amount (Lower bound)	**Precipitation LB**	mm	Qualitatve	5	Met Office
		Cloud cover		12	Average of hourly total cloud cover (Lower bound)	**Mean cloud cover LB**	%	Qualitatve	5	Met Office
	Heavy precipitation	Precipitation		1	Total precipitation amount (Upper bound) 2	**Precipitation UB**	mm	Qualitatve	5	Met Office
				2	Count of days with >= 10mm precipitation (Upper bound) 2	**Days of rain >= 10 mm UB**	Days	Qualitatve	5	Met Office
	Snow cover/ Frost cover	Temperature		13	Average of daily minimum air temperature (Lower bound)	**Minimum temperature LB**	°C	Qualitatve	5	Met Office
		Frost		14	Count of days when the minimum air temperature is below 0C	**Days of air frost UB**	Days	Qualitatve	5	Met Office
				15	Count of days when the grass minimum temperature is below 0C	**Days of ground frost UB**	Days	Qualitatve	5	Met Office
		Snow		16	Count of days with sleet or snow falling	**Days of sleet or snow falling UB**	Days	Qualitatve	5	Met Office
				17	Count of days with greater than 50% of the ground covered by snow at 0900 UTC	**Days of snow lying UB**	Days	Qualitatve	5	Met Office
	Fog event	Seasonal changes of fog events			No indicator					
	Wind event	Seasonal changes to windspeed and direction			No indicator					
Sensitivity	Environmental Sensitivity	Surrounding Environment		18	Number of Special Areas of Conservation in port county	**NumberSAC**	N/A	Quantitative	N/A	JNCC
		Air Quality		19	Count of days with Air Quality Daily index >= 5	**AQDailyIndex**	Days	Quantitative	N/A	DEFRA
		Hazmat		20	Brownfield ratio higher than 0.5%		%	Qualitatve	2	NHF
	Built Asset Sensitivity	Land-Side Built Asset Sensitivity			No indicator					
		Water-Side Built Asset Sensitivity	Shelter	21	Shelter Afforded	**ShelterAfford**	N/A	Qualitatve	5	World Port Index
			Channel limitations	22	Presence or absence of entrance restrictions	**EntranceRestrictions**	N/A	Qualitatve	5	World Port Index
				23	Presence or absence of overhead limitations	**OverheadLimits**	N/A	Qualitatve	2	World Port Index
			Water depth	24	The controlling depth of the principal or deepest channel at chart datum	**ChannelDepth**	m	Qualitatve	5	World Port Index
				25	The greatest depth at chart datum alongside the respective wharf/pier	**PierDepth**	m	Qualitatve	5	World Port Index
			Tidal range	26	Mean tide range at the port	**TideRange**	m	Quantitative	N/A	World Port Index
	Economic Sensitivity	Regional Economic Sensitivity		27	Gross domestic product (GDP)	**GDP**	£million	Quantitative	N/A	Eurostat
				28	Gross Value Added per head per month	**GVA**	%	Quantitative	N/A	ONS
		Seaport Economic Sensitivity		29	Seaport market share in the UK	**SeaportMarketShare**	%	Quantitative	N/A	DfT
				30	Seaport Direct employment	**SeaportEmployment**	number of jobs	Quantitative	N/A	Maritime UK
	Social Sensitivity	Surrounding Population's Sensitivity		31	Socio-spatial vulnerability index - flood	**SsVIflood**	N/A	Quantitative	N/A	Climate Just
				32	Socio-spatial vulnerability index - heat	**SsVIheat**	N/A	Quantitative	N/A	Climate Just
		Surrounding Structures / Asset Sensitivity		33	UK House Price Index	**HousePrice**	£	Quantitative	N/A	HM Land Registry
Adaptive Capacity	Operational Efficiency	Seaport Operational Efficiency			No indicator					
		Efficiency of Transport Connections		34	Congestion index	**CongestionIndex**	N/A	Qualitatve	5	TomTom N.V.
				35	Presence of direct rail connections	**RailConnection**	N/A	Qualitatve	4	World Port Index
	Waterside Capacity	Vessel		36	Harbor size	**HabourSize**	N/A	Qualitatve	4	World Port Index
		Passenger		37	Total passenger traffic	**SeaportPassengerTraffic**	N/A	Quantitative	N/A	DfT
		Cargo		38	Total freight traffic	**SeaportFreightTraffic**	Tonnage	Quantitative	N/A	DfT
	Landside Capacity	Flexibility		39	Number of berths	**NumberBerth**	N/A	Quantitative	N/A	UK Ports
				40	Number of crane types	**NumberCraneType**	N/A	Qualitatve	4	World Port Index
				41	Number of lift types	**NumberLiftType**	N/A	Qualitatve	5	World Port Index
		Seaport Planning		42	Do Seaport Master Plans consider resilience?	**MasterPlan**	yes / no	Qualitatve	2	EA
				43	Do State and Local Adaptations Plans consider resilience?	**LocalPlan**	yes / no	Qualitatve	2	EA
				44	Does the seaport have sustainability plan?	**SustainabilityPlan**	yes / no	Qualitatve	2	EA
		Seaport Growth		45	Positive annual percentage change in passenger or freight	**%changeSeaportPassengerFreight**	yes / no	Qualitatve	2	DfT
				46	Positive annual percentage change in seaport market share	**%changeSeaportMarketshare**	yes / no	Qualitatve	2	DfT

Annex 3 CRI framework for airports

Category	Sub-category	Sub-sub-category	No.	Description	Indicator	Units	Types	Level	Data Source
Exposure	Damaging cyclone	Precipitation	1	Total precipitation amount (Upper bound) 1	**Precipitation UB**	mm	Qualitatve	5	Met Office
			2	Count of days with >= 10mm precipitation (Upper bound) 1	**Days of rain >= 10 mm UB**	Days	Qualitatve	5	Met Office
		Wind	3	Average of hourly mean wind speed at a height of 10 m above ground level (Upper bound)	**Mean wind speed UB**	knots	Qualitatve	5	Met Office
		Pressure	4	Average of hourly mean sea level pressure (Lower bound)	**Mean sea level pressure LB**	kts	Qualitatve	5	Met Office
			5	Average of hourly vapour pressure (Lower bound)	**Mean vapour pressure LB**	kts	Qualitatve	5	Met Office
		Storm Surge	6	Top 10 skew surges records 1	**Skew surges records**	m	Qualitatve	5	BODC
		Lightning	7	Days of thunder in a month	**Days of thunder**	Days	Qualitatve	7	Met Office
	Sea-level rise	Sea level	8	Top 10 sea level records	**Sea level recrods**	m	Qualitatve	5	BODC
		Storm Surge	6	Top 10 skew surges records 2	**Skew surges records**	m	Qualitatve	5	BODC
	Warming trend/ Extreme temperature/ Drought	Temperature	9	Average of daily maximum air temperature (Upper bound)	**Maximum temperature UB**	°C	Qualitatve	5	Met Office
		Relatitive humidity	10	Average of hourly relative humidity (Lower bound)	**Relative humidity LB**	%	Qualitatve	5	Met Office
		Precipitation	11	Total precipitation amount (Lower bound)	**Precipitation LB**	mm	Qualitatve	5	Met Office
		Cloud cover	12	Average of hourly total cloud cover (Lower bound)	**Cloud cover LB**	%	Qualitatve	5	Met Office
	Precipitation Hazard	Precipitation	1	Total precipitation amount (Upper bound) 2	**Precipitation UB 2**	mm	Qualitatve	5	Met Office
			2	Count of days with >= 10mm precipitation (Upper bound) 2	**Days of rain >= 10 mm UB 2**	Days	Qualitatve	5	Met Office
	Snow cover/ Frost cover	Temperature	13	Average of daily minimum air temperature (Lower bound)	**Minimum temperature LB**	°C	Qualitatve	5	Met Office
		Frost	14	Count of days when the minimum air temperature is below 0C	**Days of air frost UB**	Days	Qualitatve	5	Met Office
			15	Count of days when the grass minimum temperature is below 0C	**Days of ground frost UB**	Days	Qualitatve	5	Met Office
		Snow	16	Count of days with sleet or snow falling	**Days of sleet or snow falling UB**	Days	Qualitatve	5	Met Office
			17	Count of days with greater than 50% of the ground covered by snow at 0900 UTC	**Days of snow lying UB**	Days	Qualitatve	5	Met Office
	Fog event	Seasonal changes of fog events		No indicator					
	Wind event	Seasonal changes to wind speed and direction		No indicator					
Sensitivity	Environmental Sensitivity	Surrounding Environment	18	Number of Special Areas of Conservation in port county	**NumberSAC**	N/A	Quantitative	N/A	JNCC
		Air Quality	19	Count of days with Air Quality Daily index > 5	**AQDailyIndex**	Days	Quantitative	N/A	DEFRA
		Hazmat	20	Brownfield ratio higher than 0.5%	**Brownfield ratio**	%	Qualitatve	2	NHF
	Built Asset Sensitivity	Land-Side Built Asset Sensitivity		No indicator					
		Air-Side Built Asset Sensitivity		No indicator					
	Economic Sensitivity	Regional Economic Sensitivity	27	Gross domestic product (GDP)	**GDP**	£million	Quantitative	N/A	Eurostat
			28	Gross Value Added per head per month	**GVA per head**	£	Quantitative	N/A	ONS
		Airport Economic Sensitivity	47	Airport market share in the UK	**AirportMarketShare**	%	Quantitative	N/A	CAA
			46	Direct employment	**AirportEmployment**	number of jobs	Quantitative	N/A	HM government
	Social Sensitivity	Surrounding Population's Sensitivity	31	Socio-spatial vulnerability index - flood	**SoVIflood**	N/A	Quantitative	N/A	Climate Just
			32	Socio-spatial vulnerability index - heat	**SoVIheat**	N/A	Quantitative	N/A	Climate Just
		Surrounding Structures / Asset Sensitivity	33	UK House Price Index	**HousePrice**	£	Quantitative	N/A	HM Land Registry
Adaptive Capacity	Operational Efficiency	Airport Opperational Efficiency	49	Punctuality Statistics	**PunctualityStatistics**	min	Quantitative	N/A	CAA
		Efficiency of Transport Connections	34	Congestion index	**CongestionIndex**	N/A	Qualitatve	5	Tom Tom International
			50	Presence of direct rail connections	**AirportRailConnection**	yes / no	Qualitatve	4	Airport codes
	Air-side Capacity	Aircraft	51	Runway length	**RunwayLength**	m	Qualitatve	3	Airport codes
		Passenger	52	Total passenger traffic	**AirportPassengerTraffic**	Passenger	Quantitative	N/A	CAA
		Cargo	53	Total freight traffic	**AirportFreightTraffic**	Tonnage	Quantitative	N/A	CAA
	Land-side Capacity	Flexibility	54	Number of runways	**NumberRunway**	N/A	Qualitatve	2	Airport codes
			55	Number of terminals	**NumberTerminal**	N/A	Qualitatve		Airport codes
		Airport Planning	42	Do Airport Master Plans consider resilience?	**AirportPlan**	yes / no	Qualitatve	2	EA
			43	Do State and Local Adaptations Plans consider resilience?	**LocalPlan**	yes / no	Qualitatve	2	EA
			44	Does the airport have sustainability plan?	**SustainabilityPlan**	yes / no	Qualitatve	2	EA
		Airport Growth	56	Positive annual percentage change in passenger or freight	**%changeAirportPassengerFreight**	yes / no	Qualitatve	2	CAA
			57	Positive annual % annual % change in airport market share	**%changeAirportMarketshare**	yes / no	Qualitatve	2	CAA

Annex 4 Consistent ratio of CRI framework for seaports

CRI ConI = 0.0040 ConR = 0.0069	Exposure ConI = 0.0531 ConR = 0.0429	Damaging cyclone ConI = 0.0130 ConR = 0.0116	Precipitation N/A
			Wind N/A
			Pressure N/A
			Storm Surge N/A
			Lightning N/A
		Sea-level rise N/A	Sea level N/A
			Storm Surge N/A
		Warming trend/ Extreme temperature/ Drought ConI = 0.0465 ConR = 0.0517	Temperature N/A
			Relative humidity N/A
			Precipitation N/A
			Cloud cover N/A
		Precipitation Hazard N/A	Precipitation N/A
		Snow cover/ Frost cover ConI = 0.0465 ConR = 0.0517	Temperature N/A
			Frost N/A
			Snow N/A
		Fog event N/A	Seasonal changes of fog events N/A
		Wind event N/A	Seasonal changes to wind speed and direction N/A
	Sensitivity ConI = 0.0530 ConR = 0.0913	Environmental Sensitivity ConI = 0.008 ConR = 0.0013	Surrounding Environment N/A
			Air Quality N/A
			Hazmat N/A
		Built Asset Sensitivity N/A	Land-Side Built Asset Sensitivity N/A
			Sea-Side Built Asset Sensitivity CI = 0.0490 ConR = 0.0544
		Economic Sensitivity N/A	Regional Economic Sensitivity N/A
			Seaport Economic Sensitivity N/A
		Social Sensitivity N/A	Surrounding Population's Sensitivity N/A
			Surrounding Structures / Asset Sensitivity N/A
	Adaptive Capacity ConI = 0.0066 ConR = 0.0113	Operational Efficiency	Seaport Opperational Efficiency N/A
			Efficiency of Transport Connections N/A
		Waterside Capacity ConI = 0.0199 ConR = 0.0343	Aircraft N/A
			Passenger N/A
			Cargo N/A
		Land-side Capacity ConI = 0.0641 ConR = 0.1105	Flexibility ConI = 0.0084 ConR = 0.0145
			Airport Planning ConI = 0.0072 ConR = 0.0124
			Airport Growth N/A

Annex 5 Consistent ratio of CRI framework for airports

CRI ConI = 0.0530 ConR = 0.0913	Exposure ConI = 0.0301 ConR = 0.0243	Damaging cyclone ConI = 0.0150 ConR = 0.0134	Precipitation N/A
			Wind N/A
			Pressure N/A
			Storm Surge N/A
			Lightning N/A
		Sea-level rise N/A	Sea level N/A
			Storm Surge N/A
		Warming trend/ Extreme temperature/ Drought ConI = 0.0465 ConR = 0.0517	Temperature N/A
			Relative humidity N/A
			Precipitation N/A
			Cloud cover N/A
		Precipitation Hazard N/A	Precipitation N/A
		Snow cover/ Frost cover ConI = 0.0001 ConR = 0.0002	Temperature N/A
			Frost N/A
			Snow N/A
		Fog event N/A	Seasonal changes of fog events N/A
		Wind event N/A	Seasonal changes to wind speed and direction N/A
	Sensitivity ConI = 0.0367 ConR = 0.0407	Environmental Sensitivity ConI = 0.0020 ConR = 0.0035	Surrounding Environment N/A
			Air Quality N/A
			Hazmat N/A
		Built Asset Sensitivity N/A	Land-Side Built Asset Sensitivity N/A
			Sea-Side Built Asset Sensitivity N/A
		Economic Sensitivity N/A	Regional Economic Sensitivity N/A
			Seaport Economic Sensitivity N/A
		Social Sensitivity N/A	Surrounding Population's Sensitivity N/A
			Surrounding Structures / Asset Sensitivity N/A
	Adaptive Capacity ConI = 0.0001 ConR = 0.0002	Operational Efficiency	Seaport Opperational Efficiency N/A
			Efficiency of Transport Connections N/A
		Air-side Capacity ConI = 0.0032 ConR = 0.0055	Aircraft N/A
			Passenger N/A
			Cargo N/A
		Land-side Capacity ConI = 0.0035 ConR = 0.0060	Flexibility
			Airport Planning ConI = 0.0072 ConR = 0.0159
			Airport Growth N/A

Annex 6 List of the 136 port cities analysed by United Nations

ID	Region	CR	Country	Agglomeration
1	AFRICA	3	ALGERIA	Algiers
2	AFRICA	3	ANGOLA	Luanda
3	S. AMERICA	4	ARGENTINA	Buenos Aires
4	AUSTRALASIA	1	AUSTRALIA	Adelaide
5	AUSTRALASIA	1	AUSTRALIA	Brisbane
6	AUSTRALASIA	1	AUSTRALIA	Melbourne
7	AUSTRALASIA	1	AUSTRALIA	Perth
8	AUSTRALASIA	1	AUSTRALIA	Sydney
9	ASIA	4	BANGLADESH	Chittagong
10	ASIA	4	BANGLADESH	Dhaka
11	ASIA	4	BANGLADESH	Khulna
12	S. AMERICA	3	BRAZIL	Santos
13	S. AMERICA	3	BRAZIL	Belem
14	S. AMERICA	3	BRAZIL	Fortaleza
15	S. AMERICA	4	BRAZIL	Vitoria
16	S. AMERICA	3	BRAZIL	Maceio
17	S. AMERICA	3	BRAZIL	Natal
18	S. AMERICA	3	BRAZIL	Recife
19	S. AMERICA	3	BRAZIL	Porto Alegre
20	S. AMERICA	4	BRAZIL	Rio de Janeiro
21	S. AMERICA	3	BRAZIL	Salvador
22	AFRICA	3	CAMEROON	Douala
23	N. AMERICA	1	CANADA	Montreal
24	N. AMERICA	2	CANADA	Vancouver
25	ASIA	4	CHINA	Dalian
26	ASIA	4	CHINA	Fuzhou
27	ASIA	4	CHINA	Guangzhou
28	ASIA	4	CHINA	Shenzhen
29	ASIA	4	CHINA	Hangzhou
29	ASIA	4	CHINA	Ningbo
30	ASIA	4	CHINA	Qingdao
31	ASIA	4	CHINA	Shanghai
32	ASIA	4	CHINA	Taipei
33	ASIA	4	CHINA	Tianjin
34	ASIA	4	CHINA	Wenzhou
35	ASIA	4	CHINA	Xiamen
36	ASIA	3	CHINA	Yantai
37	ASIA	4	CHINA	Zhanjiang
38	ASIA	2	CHINA, HONG KONG SAR	Hong Kong
39	S. AMERICA	3	COLOMBIA	Barranquilla
40	AFRICA	4	CÔTE D'IVOIRE	Abidjan
41	N. AMERICA	3	CUBA	Havana

42	ASIA	3	DEM Republic of Korea	Nampo
43	EUROPE	1	DENMARK	Copenhagen
44	N. AMERICA	3	DOMINICAN REPUBLIC	Santo Domingo
45	S. AMERICA	4	ECUADOR	Guayaquil
46	AFRICA	4	EGYPT	Alexandria
47	EUROPE	1	FINLAND	Helsinki
48	EUROPE	1	FRANCE	Marseille
49	EUROPE	2	GERMANY	Hamburg
50	AFRICA	3	GHANA	Accra
51	EUROPE	1	GREECE	Athens
52	AFRICA	3	GUINEA	Conakry
53	N. AMERICA	3	HAITI	Port-au-Prince
54	ASIA	4	INDIA	Chennai
55	ASIA	4	INDIA	Cochin
56	ASIA	4	INDIA	Kolkata
57	ASIA	4	INDIA	Mumbai
58	ASIA	4	INDIA	Surat
59	ASIA	3	INDIA	Visakhapatnam
60	SE ASIA	4	INDONESIA	Jakarta
61	SE ASIA	4	INDONESIA	Palembang
62	SE ASIA	3	INDONESIA	Surabaya
63	SE ASIA	3	INDONESIA	Ujung Pandang
64	EUROPE	1	IRELAND	Dublin
65	EUROPE	1	ISRAEL	Tel Aviv
66	EUROPE	1	ITALY	Naples
67	SE ASIA	2	JAPAN	Fukuoka
68	SE ASIA	2	JAPAN	Hiroshima
69	SE ASIA	2	JAPAN	Nagoya
70	SE ASIA	2	JAPAN	Osaka
71	SE ASIA	2	JAPAN	Sapporo
72	SE ASIA	1	JAPAN	Tokyo
73	ASIA	1	KUWAIT	Kuwait City
74	EUROPE	1	LEBANON	Beirut
75	AFRICA	1	LIBYAN ARAB JAMAHIRIYA	Benghazi
76	AFRICA	1	LIBYAN ARAB JAMAHIRIYA	Tripoli
77	SE ASIA	3	MALAYSIA	Kuala Lumpur
78	AFRICA	3	MOROCCO	Casablanca
78	AFRICA	3	MOROCCO	Rabat
79	AFRICA	4	MOZAMBIQUE	Maputo
80	ASIA	4	MYANMAR	Yangon
81	EUROPE	2	NETHERLANDS	Amsterdam
82	EUROPE	2	NETHERLANDS	Rotterdam
83	AUSTRALASIA	1	NEW ZEALAND	Auckland
84	AFRICA	4	NIGERIA	Lagos

85	ASIA	3	PAKISTAN	Karachi
86	S. AMERICA	3	PANAMA	Panama City
87	S. AMERICA	3	PERU	Lima
88	SE ASIA	3	PHILIPPINES	Davao
89	SE ASIA	4	PHILIPPINES	Manila
90	EUROPE	1	PORTUGAL	Lisbon
91	EUROPE	1	PORTUGAL	Porto
92	S. AMERICA	2	PUERTO RICO	San Juan
93	ASIA	2	REPUBLIC OF KOREA	Busan
94	ASIA	1	REPUBLIC OF KOREA	Ulsan
95	ASIA	2	REPUBLIC OF KOREA	Inchon
96	EUROPE	4	RUSSIAN FEDERATION	St Petersburg
97	ASIA	1	SAUDI ARABIA	Jeddah
98	AFRICA	3	SENEGAL	Dakar
99	SE ASIA	1	SINGAPORE	Singapore
100	AFRICA	3	SOMALIA	Mogadishu
101	AFRICA	3	SOUTH AFRICA	Cape Town
102	AFRICA	3	SOUTH AFRICA	Durban
103	EUROPE	1	SPAIN	Barcelona
104	EUROPE	1	SWEDEN	Stockholm
105	SE ASIA	4	THAILAND	Bangkok
106	AFRICA	4	TOGO	Lome
107	EUROPE	4	TURKEY	Istanbul
108	EUROPE	3	TURKEY	Izmir
109	ASIA	4	UKRAINE	Odessa
110	ASIA	2	UNITED ARAB EMIRATES	Dubai
111	EUROPE	1	UNITED KINGDOM	Glasow
112	EUROPE	2	UNITED KINGDOM	London
113	AFRICA	3	UNITED REPUBLIC OF TANZANIA	Dar es Salaam
114	N. AMERICA	2	UNITED STATES OF AMERICA	Baltimore
115	N. AMERICA	2	UNITED STATES OF AMERICA	Boston
116	N. AMERICA	2	UNITED STATES OF AMERICA	Houston
117	N. AMERICA	2	UNITED STATES OF AMERICA	Los Angeles
118	N. AMERICA	2	UNITED STATES OF AMERICA	Miami
119	N. AMERICA	2	UNITED STATES OF AMERICA	New Orleans
120	N. AMERICA	2	UNITED STATES OF AMERICA	New York
121	N. AMERICA	2	UNITED STATES OF AMERICA	Philadelphia
122	N. AMERICA	1	UNITED STATES OF AMERICA	Portland
123	N. AMERICA	2	UNITED STATES OF AMERICA	Providence
124	N. AMERICA	1	UNITED STATES OF AMERICA	San Diego
125	N. AMERICA	2	UNITED STATES OF AMERICA	San Francisco
126	N. AMERICA	1	UNITED STATES OF AMERICA	San Jose
127	N. AMERICA	1	UNITED STATES OF AMERICA	Seattle
128	N. AMERICA	2	UNITED STATES OF AMERICA	Tampa

129	N. AMERICA	2	UNITED STATES OF AMERICA	Virginia Beach
130	N. AMERICA	1	UNITED STATES OF AMERICA	Washington
131	S. AMERICA	3	URUGUAY	Montevideo
132	S. AMERICA	3	VENEZUELA	Maracaibo
133	ASIA	4	VIETNAM	Haiphong
134	ASIA	4	VIETNAM	Ho Chi Minh City

Note: "CR" means risk of a territory being affected by climate change, and the definition of CR groups: "1" = Lowest risk scenario, "2" = Managed-risk scenario, "3" = Mismanaged-risk scenario, and "4" = Highest risk scenario

Annex 7 List of the 20 transit port cities

ID	Region	Country	Agglomeration
135	AFRICA	MOROCCO	Tangier
136	ASIA	OMAN	Salalah
137	SE ASIA	SRI LANKA	Colombo
138	EUROPE	SPAIN	Algeciras
139	EUROPE	SPAIN	Valencia
140	ASIA	INDIA	Krishnapatnam
141	EUROPE	MALTA	Marsaxlokk
142	S. AMERICA	BRAZIL	Navegantes
143	AFRICA	EGYPT	Port Said East
144	AUSTRALASIA	NEW ZEALAND	Tauranga
145	AFRICA	MOROCCO	Tangier
146	ASIA	OMAN	Salalah
147	SE ASIA	SRI LANKA	Colombo
148	EUROPE	SPAIN	Algeciras
149	EUROPE	SPAIN	Valencia
150	ASIA	INDIA	Krishnapatnam
151	EUROPE	MALTA	Marsaxlokk
152	S. AMERICA	BRAZIL	Navegantes
153	AFRICA	EGYPT	Port Said East
154	AUSTRALASIA	NEW ZEALAND	Tauranga