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Under-water noise pollution sources, mitigation measures in commercial vessels: the trade-off analysis in the case of study for trans mountain project, Port of Vancouver, Canada.

Seyedvahid Vakili

WORLD MARITIME UNIVERSITY
Malmö, Sweden

UNDER-WATER NOISE POLLUTION SOURCES,MITIGATION MEASURES IN COMMERCIAL VESSELS:

THE TRADE-OFF ANALYSIS IN THE CASE OF STUDY FOR TRANS MOUNTAIN PROJECT, PORT OF VANCOUVER, CANADA.

By

Seyedvahid Vakili
IRAN

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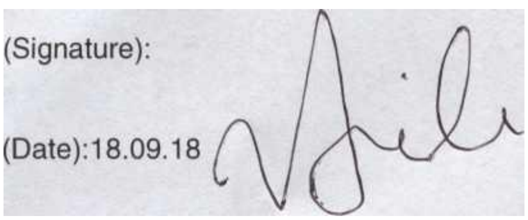
DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.



Supervised by: Prof. A. Ölcer (MEM)

World Maritime University

Abstract

Shipping is the most efficient type of transportation and plays a significant role in global trade. However, it has some negative externalities and creates environmental pollution. With the growth of shipping, the potential for low-frequency noise increases along with its negative effects such as impacts on marine species and threat to sustainable shipping, e.g. its intensity has been doubling in the North Pacific Ocean every decade for the past 60 years and it is predicted to increase by 87–102% on average by 2030. In contrast to other environmental issues, the underwater noise is not visible, so to raise awareness and show its negative impacts, a scientific approach and data collection are required. While awareness of the society in respect of the other pollutions such as oil, dangerous goods, noxious liquids substances, sewage, and air has been raised and those issues are regulated properly, society has not been familiar with under-water noise pollution and it has not been regulated properly.

As such, legal gaps exist this study is a holistic approach to UWN pollution. The main sources and the ways to mitigate UWN pollution and its effect on sustainable shipping will be reviewed. Meanwhile, with reference to the previous environmental issues and present information and data collection, the general trends for the future of UWN pollution will be suggested. Moreover, in the case study (the Trans Mountain Project (TMP)), mitigation measures to reduce the negative impacts of the growth of shipping in the Haro Strait will be suggested. Furthermore, by creating four scenarios and modelling, simulations, utilizing the MCDM (MADM) algorithms, and TOPSIS techniques the trade-off between the environmental (noise and Co2 emission) and economical (fuel cost) aspects of the project will be conducted to enhance the Decision Support System (DSS). This will help the decision makers to have a multi-dimensional thinking instead of the single dimensional thinking in addressing and tackling the negative externalities of the TMP in the area. Moreover, at the end of each scenario, a sensitivity analysis will be conducted to provide a clean environment for decision makers.

Keywords: Cavitation, Commercial ships, Co2 emission, Fuel consumption, Fuel cost, inflow, Machinery, MADM, Marine species, Maximization, Mitigation measures, Model, Optimize, Pollution, Propeller, Radiation, Scenario, Sensitivity analysis, Ship's hull, Simulation, Tankers, TOPSIS, Trade-off, Trans Mountain Project (TMP), Tug, Underwater Noise (UWN), Wake.

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I am also grateful to Transport of Canada for providing me with the required data in respect of the Trans Mountain Project and in the end, I would like to express my appreciation to the class MEM, the lecturers and my colleagues, who I had a great and fruitful academic year with them.

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Abbreviations and symbols

ABC Air Bubble Curtain
ACCOBAMS Agreement for the conservation of cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic waters
BEM Boundary Element Method
BTSS Boston Traffic Separation Scheme power co-efficient
Cb Block co-efficient
Ci Relative closeness
CIS Cavitation Inception Speed
CLT Contracted and Loaded Tip
CFD Computational Fluid Analysis
CPP Controllable Pitch Propeller
Co2 Carbon Dioxide
CSR Corporate Social Responsibility
Cv Coefficient corresponding to the slope of the curve
dB Decibel
D.C Direct Current
DSS Decision Support System
ECDIS Electronic Chart Display and Information System
ECHO Enhancing Cetacean Habitat and Observation
EEDI Energy Efficiency Design Index
EFD Experimental Fluid Dynamics
EU European Union
FEA Finite Element Analysis
FPP Fixed pitch Propeller
GDP Gross Domestic Product
HNS Hazardous and Noxious Substances
HZ Hertz
IFAW The International Fund for Animal Welfare
IMO International Maritime Organization
IPCC Intergovernmental Panel on Climate Change
LNG Liquid Natural Gas
MCDM Multiple Criteria Decision Making
MADM Multiple Attributes Decision Making
MARPOL The International Convention for the Prevention of Pollution from Ships convention

MD	Mewis duct
MEPC	Marine Environment Protection Committee
MSFD	Marine Strategy Framework Directive
MSL	Monopole Source Level
NOAA	National Oceanic and Atmospheric Administration
OECD	Organization for Economic Co-operation and Development
OSPAR	Oslo/Paris convention
PDCA	Plan–Do–Check–Act
PH	Potential of Hydrogen
PID	Propulsion Improving Devices
RPM	Revolutions per minute
SCR	Selective Catalytic Reduction
SEA	Statistical Energy Analysis
SEEMP	Ship Energy Efficiency Management Plan
SL	source level
SRKW	Southern Resident Killer Whales
SOFAR	Sound Fixing and Ranging
SOLAS	International Convention for the Safety of Life At Sea
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TMP	Trans Mountain Project
UN	United Nation
UNCLOS	United Nations Convention for the Law of the Sea
UNSDG	United Nations Sustainable Development Goal
UWN	Under-Water Noise
UWNMP	Under Water Noise Management Plan
VFPA	Vancouver Fraser Port Authority
W.E.D	Wake Equalizing Duct
WMU	World Maritime University

Chapter 1

1. Introduction

1.1 Background

A rapidly expanding human population has been the main driver for many recent human issues. Moreover, industrialization, rapid urbanization, and use of fossil fuels have led to various environmental problems such as global warming, ocean acidification, sea level rise (Stocker, 2014), and also more chemicals and wastes introduced to the environment (Halpern et al., 2008; Lazar & Gračan, 2011).On the other hand, more resources are required to support the population for food; more fish is harvested, and more raw materials are exploited (Vitousek et al. 1997). This has caused a boom in world trade and demand for transportation, accordingly. Seaborne trade has grown by a factor of 4 since 1970 and has doubled in the last two decades (Tournadre, 2014) and now, with the contribution of 90% of global trade, shipping is the most cost-effective and efficient type of transportation (Buhaug et al., 2009).

Shipping is a complex system with different stakeholders who have interrelations and interactions with each other. Although the ship has played a great role in the improvement of civilization and the welfare of the human, it has negative externalities on the environment. Some of the negative externalities are visible and can be detected immediately like oil pollution, and others are not visible and need a scientific approach to collect data and make them visible, like air pollution. Anthropogenic noise is classified in the latter case.

Sound is a type of **energy** and noise is a form and level of environmental sound that is considered likely to offend, confound or even harm humans or animals and/or used to describe sound from a source that does not transmit significant biological information (Southhall, 2005).

In accordance with the United Nations Convention on the Law of the Sea (UNCLOS) Article 1 Part 1,

> pollution of the marine environment means the introduction by man, directly or indirectly, of substances or **energy** into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities.

In this respect, noise should be considered as a Pollution. Also, in accordance with articles 194(Measures to prevent, reduce and control pollution of the marine environment) and 196(Use of technologies or introduction of alien or new species) all measures to prevent, mitigate, and control underwater pollution, including preservation of the fragile ecosystem, and habitats of depleted, endangered and all other marine forms should be considered (UNCLOS, 1982).

Many types of ship pollution like oil, chemicals, and air have been regulated by IMO. Although SOLAS regulation (II-1/3-12), which entered into force on July 1, 2014, targeted the reduction of onboard noise and protection of ship's personnel from excessive noise (Beltrán, Salinas & Moreno, 2014), there is only a guideline for the reduction of underwater noise from commercial shipping (IMO-MEPC,2014).However, there are some regional actions that take UWN into consideration, such as the EU Marine Strategy Framework Directive (MSFD)(Van der Graaf, 2012).

In the underwater environment, noise is a very important and essential factor. Many mammals and fish species use sound to find mates, avoid hazards and even for navigation (OSPAR, 2009). In the ambient environment, different kinds of noise from different sources exist. Ambient noise is usually defined as background sound that compounds a broad range of individual sources but the main source may not be identified easily (Hildebrand, 2005). The ambient acoustic environment of the ocean masks the biological sounds and is highly variable with different levels of frequency (10-300Hz) (Leaper & Renilson,2012) and can be considered as pollution with a potential to impact not only the marine ecosystem (Williams et al., 2015),but can also have a socio-economic effect on human life.

According to Hildebrand (2004), sound is divided into:

1- Natural sound in the ocean e.g. Wind Sea, Swell, Bubble, distribution, Current, precipitation, ice cover marine life, and

2-Anthropogenic sound e.g. large commercial ships, seismic exploration devices, military sonar, polar icebreaking, offshore drilling, small ships, and dredging. In each of these activities, noise emission in the ocean has a disturbance effect on marine species.

1.2 Problem Statement and Motivation

Prior to industrialization, anthropogenic noise in the ocean was negligible, but with the increase of world population, booming worldwide trade, seaborne transportation has become more important. Currently, due to the growth of ships' size, fleets and transport distance, and the introduction of more shipping routes, the potential for low-frequency noise has increased. As shown in Figure 1.1, between 1955 and 2000, not only the number of global merchant ships (ships over 100 gross tonnage) increased (Kaplan & Solomon, 2016), but also the size of ships, along with more powerful propulsion growth which led to noisier ships introduced to the ocean (Arveson & Vendittis, 2000) . For example, in parts of the North Pacific Ocean, due to increase in activity of commercial vessels, (low frequency) UWN has been doubling in intensity every decade for the past 60 years (Hildebrand, 2009; NRC, 2003) and in the Pacific Ocean off San Nicolas Island, California, it has been increased up to 3 decibels (dB) per decade (McDonald, Hildebrand & Wiggins, 2006). In the meantime, with respect to the combined effects of increased shipping, larger and noisier ships, and increased shipping distances, UWN could increase by 87–102% by 2030 (Kaplan & Solomon, 2016).
As per Richardson et al., (2013) marine mammals use the low frequency for their communication, which is in the same frequency as commercial vessels and low frequency Sonars. Although the underwater noise radiation of each ship is different

from the others, the majority of underwater noise from large commercial ships is generated at frequencies below 1,000 Hz (IMO-MEPC 72, 2018). The increase of UWN not only has negative environmental impacts, such as masking biological signals, injuries, behavioural reactions, and mortality in marine animals (OSPAR, 2009), but also has a negative impact on the socio-economic factors which will be discussed in Chapter 2.

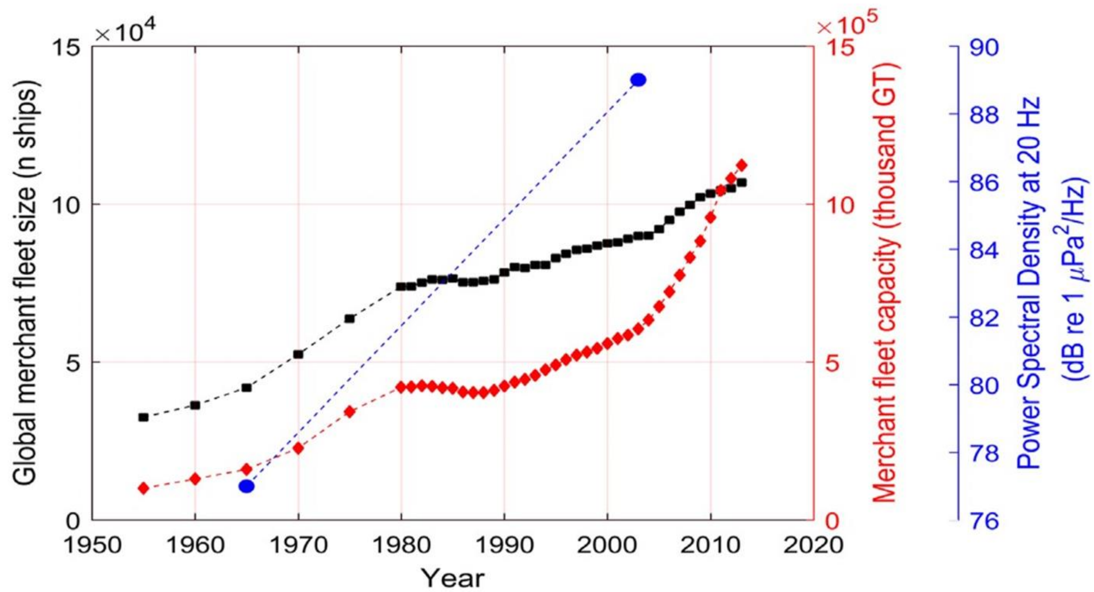


Fig 1.1. Historical size of the global merchant shipping fleet in number, gross tonnage, and ambient noise level at 20Hz in San Nicolas Island, California. Black squares: Historical size of the global merchant shipping fleet in number of ships fleet capacity. Red diamonds: thousand gross tonnage. Blue circles: two measurements of an ambient noise levels at 20Hz in San Nicolas Island, California.
Source: (Kaplan & Solomon, 2016)

It means that by decaying UWN from the commercial vessels, the low-frequency anthropogenic noise can be reduced dramatically and negative externalities affecting of UWN pollution can significantly decrease.

1.3 The dissertation

This study is a holistic approach to UWN pollution from commercial vessels and its negative impacts on the environment and marine species and also its socio-economic effect. The study gives a full picture of the issue, the main sources and the mitigation measures. In chapter 5, a case study of the Trans Mountain Project (TMP) in Vancouver port trade-off analyzes actions which should be taken to mitigate UWN in this case.

1.3.1 Dissertation objectives

The main objectives of the study are to:

1. Provide a holistic view to stakeholders of the reasons for UWN pollution, its negative impacts on the environment and its socio-economic effect.
2. Reduce anthropogenic noise pollution through commercial ships and prevent and mitigate its environmental and socio-economic effects.
3. Build models for different scenarios and trade-off between sustainability pillars (environmental (UWN pollution,Co2 emission), economic (fuel cost), and social (side effects of the UWN pollution,Co2 emission, and fuel cost)) aspects of the issue.
4. Optimize the Decision Support System (DSS) in mitigation of UWN pollution from commercial vessels by integrating four scenarios into Multi-attribute decision making (MADM) algorithms and utilizing TOPSIS techniques.

The study should be able to provide a full picture of UWN pollution, the reason for radiation, and the measures to mitigate it. Besides suggestions for the trade-off between UWN, Co2 emissions, and fuel costs, other mitigation measures for the decay of UWN pollution due to TMP are presented.

1.3.2 Methodology

For a holistic approach to the topic, a systematic and detailed literature review of various resources such as books, academic journals, reports of the IMO and other organizations, global and local projects, international seminars and workshops, and classification societies was conducted. The collected data was classified, understood and qualitative and comparative analyses were conducted. Moreover, by collecting shipping data within Haro Strait, the quantitative analysis was used to determine UWN radiation from vessels (tankers and tugs), the amount of fuel consumption, and Co2 emissions in the area. Furthermore, by creating 4 scenarios and using Monte-Carlo simulations, Multiple Attributes Decision Making (MADM) algorithms have been created. By applying the TOPSIS techniques, the best alternative based on the trade-off between UWN radiation, Co2 emission, and fuel cost has been identified.
In the final stage, by data achieved in the TOPSIS techniques, the sensitivity analysis was applied for each alternative and maximization of their C_i^* value done to find the optimum criteria of the alternatives.
In this dissertation, the Microsoft Office Excel was used for calculating and processing the achieved data. Then an original Oracle Crystal Ball software has been used to create the models and apply the MADM, TOPSIS techniques, and sensitivity analysis, accordingly.

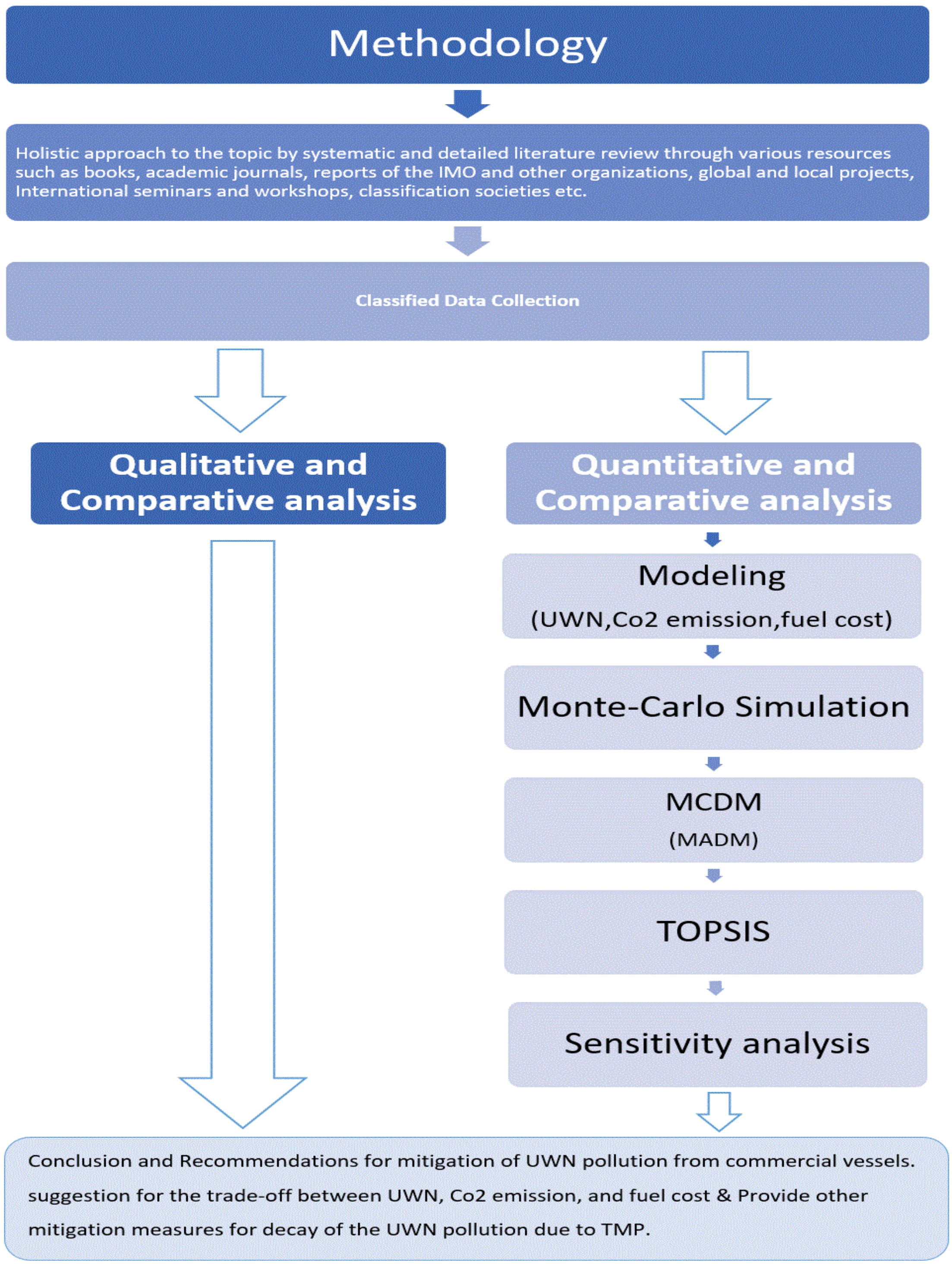


Fig 1. 2. The research methodology

1.3.3 Dissertation outline

Chapter 2 describes the effect of anthropogenic noise on marine species and the socio-economic impact of UWN radiation. Further, it explains and elaborates the relationship between UWN pollution and UNSDGs and sources of UWN pollution from the commercial vessels.

Chapter 3 presents the guidelines for reduction of UWN from commercial vessels. In this chapter, the different mitigation measures will be reviewed.

Chapter 4 elaborates the methodology that has been used for trade-off analysis in developing the case study by creating models, Scenarios, Monte-Carlo simulations, MADM, TOPSIS, and sensitivity analysis.

Chapter 5 is the case study. It illustrates the measures that can be taken in order to minimize the negative effect of the Trans Mountain Project (TMP) in the Haro Strait. It presents four scenarios to trade-off the environmental (noise and Co2 emission) and economical (fuel cost) aspects and helps the decision makers to choose the best option to minimize the negative impacts of the TMP in the area. Moreover, it presents new suggestions for the mitigation of the UWN radiation in the area.

Chapter 6 is the total conclusion and recommendation in respect to the mitigation of UWN pollution from commercial vessels. It presents the general trend in order to mitigate UWN pollution.

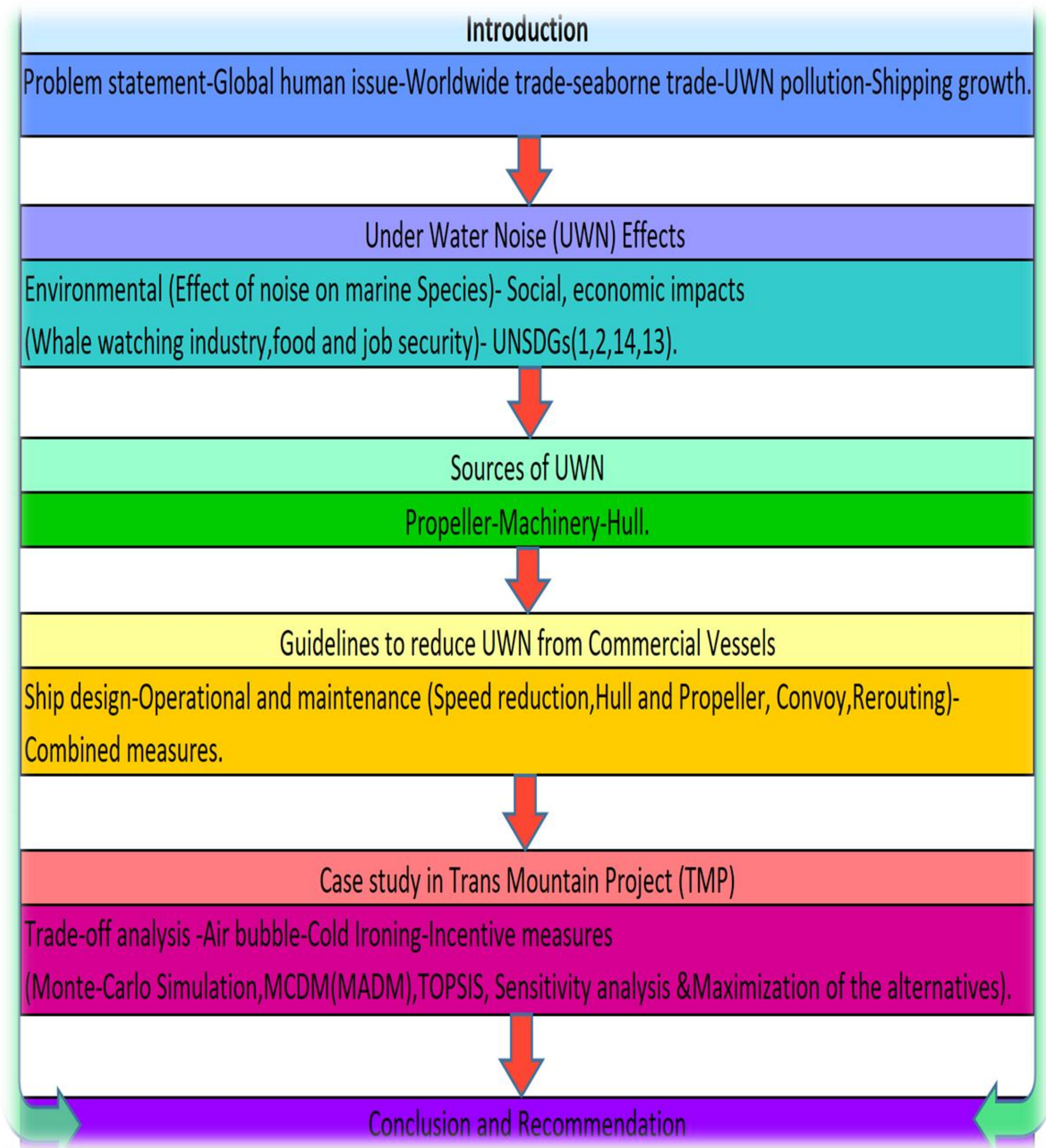


Fig 1. 3. Dissertation flow chart

Chapter 2

2. Anthropogenic noise effects and Sources of underwater noise

2.1Effect of Noise on Marine Species

Noise is a complex phenomenon and predicting its spread in the ocean is not an easy task (Hildebrand, 2009). It is the function of many variables such as water depth, the sound frequency, and water column density (density itself is the function of salinity, temperature, and pressure). Furthermore, the ocean bottom and seabed also influence the propagation of UWN radiation (Lurton & Cuchieri, 2011).
Figure 2.1 demonstrates the level and frequencies of anthropogenic and naturally occurring sound sources in the marine environment (OSPAR, 2009).

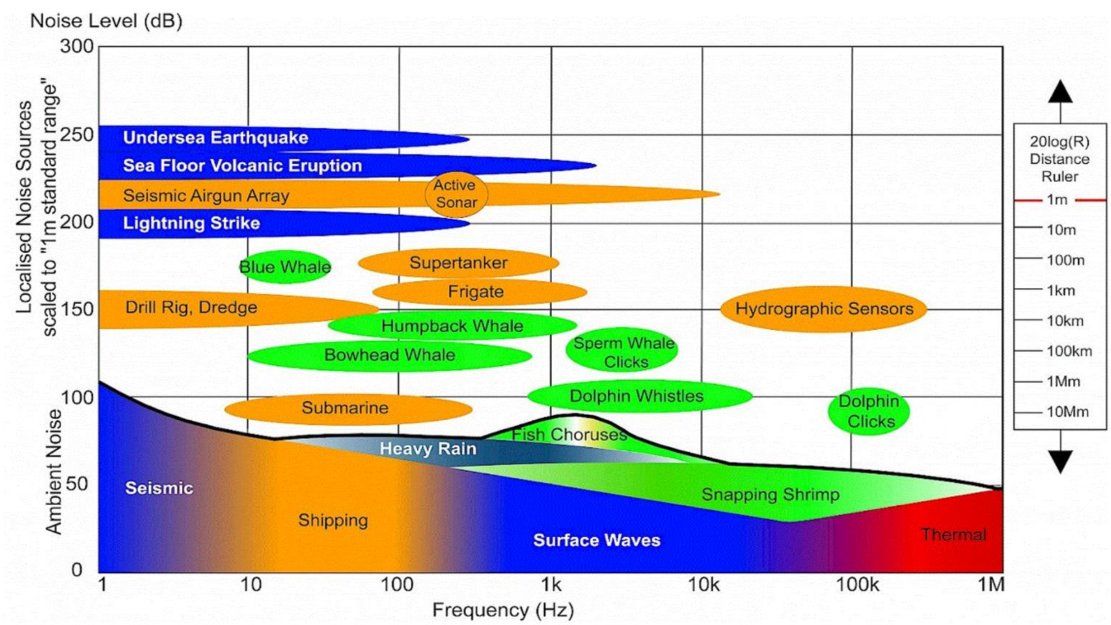


Fig 2.1. Levels and frequencies of anthropogenic and naturally occuring sound resources in the marine environment.
Source : (OSPAR,2009)

Commercial ships are present in almost all parts of the ocean and are the major anthropogenic noise producer (McKenna et al., 2013). As Figure 2.1 shows, the predominant noise from shipping is low frequency (<500 HZ) (OSPAR, 2009). Sound travels five times faster in water than in air, and the water's density can transmit noise to greater distances than in air, so UWN from commercial vessels (low frequency) extends through very large volumes of water (Abdulla, 2008) and this can happen for longer ranges in high latitudes due to SOFAR (Sound Fixing and Ranging) channel (Wright, 2008).

Anthropogenic sound can be classified as;

- Impulsive sound;
- Continuous sound ;
- Short duration, and
- Long lasting, each of which has different effects upon animals (Hawkins et al., 2015).

Impulsive ocean noise consists of intense short pulses of very loud sound, repeated over a period of time. High-powered active sonar used during military or civil operations, and seismic surveying for oil and gas exploration are some example of impulsive noise (Nolet, 2017), which produces low to high-frequency sound and causes exposure of individual marine species to high sound levels over the short period of time. Impulsive noise has a negative impact on species. Some are only on individuals like dolphins many kilometres away; however, some are on entire populations and can have immediate impacts and even trigger mortality e.g. stranding of beaked whales in the Bahamas (2000) and the Canary Islands (2002) was likely due to acoustic trauma from the use of high-intensity sonar(Cox et al., 2006).

Meanwhile, continuous noise is typically a constant buzz, generated by shipping, offshore oil and gas rigs, and offshore wind farms. It has impacts on local marine life and contributes to background noise at long range and low frequencies (Hildebrand, 2009). The short-term effects of intense sound levels may result in injury and death, and long-term effects of continuous sound can affect habitat quality and might, therefore, cause effects on animal populations (OSPAR, 2009).

All fish studied to date are able to hear sounds and also many invertebrates have been found to be able to detect sound and/or vibration and to respond to acoustic cues (Simpson et al. 2011b; Weilgart, 2017). Underwater sound is made up of both particle motion and acoustic pressure. While sound pressure in the marine environment naturally acts in all directions, particle motion is an oscillation back and forward in a particular direction (ISO/ DIS, 2016). Species exposed to ocean noise can experience damage from either component of sound-pressure or particle motion. For invertebrates and fish, which have directional hearing systems, the particle motion is more important than the sound pressure (Popper et al., 2014; Hawkins et al., 2015; Nedelec et al., 2016).However, many species and all marine mammals can detect sound pressure (Hawkins & Popper, 2017).

Underwater noise impacts on physiology and can cause poor growth rates, behavioural change, breeding pattern changes, decreased immunity, and low reproductive rates of marine species (Borsani et al., 2006; Rowe et al., 2008; Karasalo et al., 2017; Stanley et al., 2017; Weilgart, 2017). The anatomical impacts of noise on the marine species can include abnormal development or malformations, hearing loss, or injured vital organs, which can result in stranding, disorientation, and death. Some animals may recover from behavioural or physiological impacts, but other impacts, such as changing the DNA, or genetic material, or injury to vital organs, are irreversible (Kight & Swaddle, 2011). Moreover, noise exposure may affect the feeding behaviour of species but the amount of reaction and admission is different between individuals, and presence of other species may change the effects (Magnhagen, et al., 2017). Additionally, factors such as stress, distraction, confusion, and panic, can affect reproduction and growth rates of many marine species, in turn influencing the long-term welfare of populations (Williams et al., 2015), and causing changes in movement and migration of patterns or even complete abandonment of species from the polluted area (Kelly et al.,1988 ; Borsani et al., 2006). Table 2.1 demonstrates the impact and effects of the underwater noise on marine species.

Table 2.1. The potential impact of anthropogenic ocean noise exposure on marine species.

Impact	Effect on animal
Injury to tissues; Disruption of physiology	Damage to body tissues, such as internal haemorrhaging, injury of gas-filled organs like the swim bladder, poor immune response, stress
Masking	Obliteration of biologically important sounds including sounds from other members of the same group or population
Behavioural changes	Interruption of normal activities including feeding, reproduction, schooling, migration, and displacement from favoured areas
These effects will vary depending on various factors such as the noise level, distance, and other contextual variables.	

Source: (Hawkins and Popper, 2014)

Cetaceans are acoustic animals and many of their primary mechanisms are conducted by sound (Wright et al., 2007). Noise is an important factor for them in the water and they use different levels of noise to communicate. They rely heavily on sound to exploit and investigate the environment, navigate, communicate, detect hazards (Greene & Moore, 1995), find prey and avoid obstacles, predators, and other hazards (Towers, 2018).In comparison with other ocean species, acoustic communication and perception in mammals are well developed .Whale ears are mechanically tuned towards low frequencies and only detect acoustic pressure (Nedelec et al., 2016). They can also produce low-frequency ranges of noise (below 1000 Hz), which can travel long distances underwater (Jasny, 1999).However, due to noise pollution (vessel noise), their acoustic signals are masked over large areas (Hildebrand, 2005; Gabriele et al., 2018) and their communication range decreases dramatically (Maglio, 2013).

Noise pollution is a novel environmental phenomena for mammals and they cannot cope with it (Rabin & Greene, 2002). Moreover, the effects of acoustic disturbance can be greater when combined with other threats (COSEWIC, 2011). Meanwhile, the extent of impacts depends on the level of the sound received, the geographical areas, and the extent of the areas in which ship noise might impact marine mammals (Pine, 2018). Loud sounds may affect the hearing of mammals temporarily or permanently (NRC, 2003). However, the hearing sensitivity varies from species to species and even among individuals of the same species (Houser and Finneran, 2006). Table 2.2 demonstrates the effects of the different sound levels on marine mammals.

Table 2.2. The effects of different received sound levels on mammals.

Source level(SL) of received sound	Effects on Mammals
120dB	Behavioral problems and changes
150dB	Intensive behavioral problems ,Temporary Threshold Shift(TTS) and temporarily reducing of hearing sensitivity
170-180dB	Permanent Threshold Shift(PTS), constant hearing loss, physical damage , deafness ,and death sometimes

Source: (Richardson et al., 1995)

As Table 2.2 shows, different sound levels have different impacts on mammals, from behavioural changes to death. Particular attention and study should be paid to identifying the range of frequencies utilized for communication and hearing thresholds of marine organisms and species and to minimizing the anthropogenic noise production within this frequency range (Chircop et al., 2018) in order to reduce the impacts of UWN pollution on marine species.

2.2 SOCIO-ECONOMIC impact of UWN pollution

The world population will increase by more than 2 billion to reach 9.6 billion in 2050. Meanwhile, more than 80 million people are suffering from chronic malnourishment in the world (FAO, 2014). There are billions of people in the world that rely on oceans (especially the world's poorest) to provide jobs and food. According to the OECD (2016), oceans contribute $1.5 trillion annually in value-added to the overall economy and this will double by 2030.

Fish is an extremely nutritious vital source of protein and is placed on the plates of many nations as a main dish (Ziv et al.,2012). In accordance with WWF-Germany, (2017) 800 million people depend on fish as a crucial source of food and income. Moreover, as shown in Figure 2.2 the fishing industry, and maritime and coastal tourism provide jobs to tens of millions and play a significant role in the economic growth of countries (OECD, 2016).

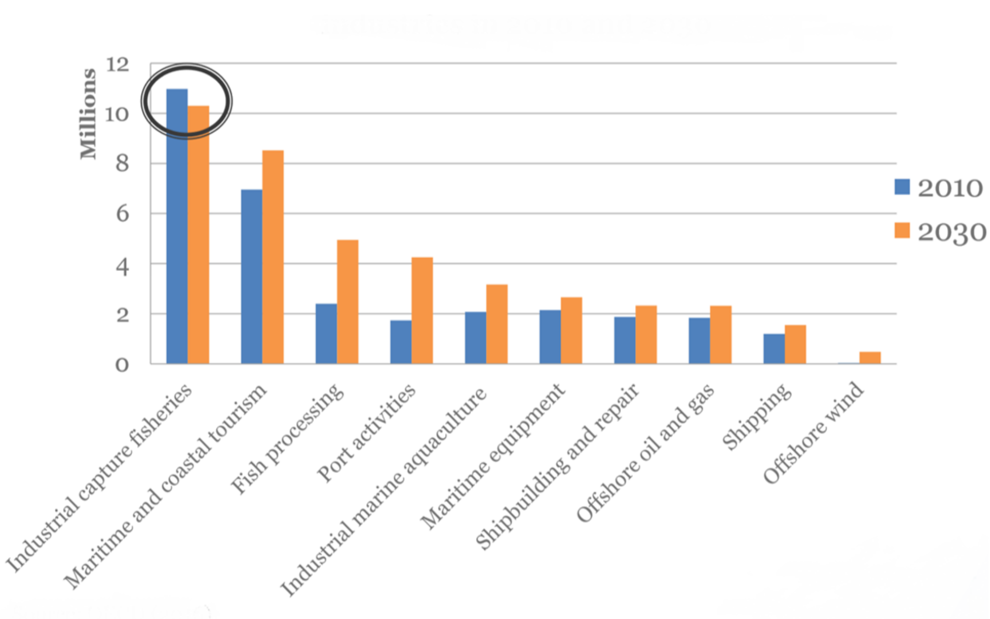


Fig 2.2. Full time equivalent employment ocean based industries in 2010 and 2030. Source: (OECD, 2016)

While the ocean has a significant role in the health and wealth of humans, human activities have negative impacts on the health of the ocean. Fish stocks have deteriorated and fishing migration is happening in different parts of the world due to climate change, ocean acidification, and overfishing (Diekert, 2012). Moreover, high traffic density in an area can increase the possibility of accidental or illegal pollution by oil or Hazardous and Noxious Substances (HNS), and introduce alien invasive species via ballast water, along with air pollution emissions, toxic substances from anti-fouling paints, marine litter pollution (OSPAR, 2017), and also UWN pollution (Abdulla, 2008). All of these have effects on fishing and ecosystem biodiversity. Although all these types of pollution have been studied for years and legislated accordingly, UWN pollution has not been studied comprehensively and there is an international legal vacancy.

UWN noise should not be underestimated in comparison to other types of pollution because of its effect on fish population, migration patterns, and reproduction (Buscaino et al., 2010; Stanely et al., 2017). It also can split the ecosystem, changing the population biology (healthy and resilient populations of various species) and ecology (different species interaction and remaining in balance) (Kunc et al., 2016). With the impact of the population biology and ecology, larger fish emigrate from the area and the fishing industry is affected (Weilgart, 2017).As a result, the food and job security of people are threatened, causing severe negative socio-economic consequences and minimizing sustainable development.

Tourism is one of the main industries, contributing trillions of dollars to the global economy. Coastal and marine tourism represents a considerable share of the industry and is an important component of the growing and sustainable economy (Brumbaugh, 2017). It supports more than 6.5 million jobs and will reach more than 8 million by 2030 (OECD, 2016). One of the most important and viable ocean tourism industries is whale watching (Lambert et al., 2010). In 2008, around 13 million people participated in whale watching tours in 119 countries (O’Connor et al., 2009).According to Cisneros-Montemayor et al., (2010), the industry has the potential to reach revenues of $ 2.5 billion yearly and support 19 000 jobs around the world. Three countries, the USA, Australia, and Canada, took more than 5 million people whale watching in 2008. Table

2.3 shows the number of people taking whale watching tours in different countries in 2008, and Table 2.4 demonstrates the annual growth rate of whale watching and its total expenditure from 1980 to 2008 (O'Connor et al., 2009).

Table 2.3. Number of whale watchers and percentage of total global whale watchers.

Country	Whale Watchers in 2008	% of total global whale watchers
USA	4,899,809	38%
Australia	1,635,374	13%
Canada	1,165,684	9%
Canary Island	611,000	5%
South Africa	567,367	4%
New Zealand	546,445	4%
China(Mainland)	307,000	2%
Argentina	244,432	2%
Brazil	228,946	2%
Scotland	223,941	2%
Total	10,506,620	81%
Global Total	12,977,218	100%

Source: (O'Connor et al., 2009)

Table 2.4. The number of whale watchers, average annual growth, direct and total expenditure in whale watching industry.

Year	Number of whale watchers	Average annual growth rate	Direct Expenditure millions	Total Expenditure millions
1981	40,000		$4.10	$14
1988	1,500,000	20.80%	$11-16	$38.5-56
1991	4,046,957	39.20%	$77	$317.90
1994	5,425,506	10.30%	$122.40	$504.30
1998	9,020,196	13.60%	$299.50	$1,049
2008	12,977,218	3.70%	$872.70	$2,113.10

Source: (O'Connor et al., 2009)

The Haro Strait is a good example of the interaction between UWN pollution and the tourism industry. The Strait, especially during summer, is one of the main places for whale watching (O'Connor et al., 2009) and it has a high shipping traffic density. The high traffic density in the area can have a negative effect on the presence of whales in the area. UWN pollution is one of the sources of pollution from ships that can cause disturbance, injury and even death of whales (Joy et al., 2017). While other types of pollutions such as the oil, plastic, and air are internationally legislated and monitored, there is no international rule for mitigation of UWN from commercial vessels. This legal gap has a negative effect on the whale watching and tourism industries and causes socio-economic problems by threatening job security.

In 2015, the United Nations(UN) agreed 169 targets in 17 goals to eliminate extreme poverty and hunger, promote economic growth and prosperity, improve health and education and protect the planet, under the name United Nations Sustainable Development Goals (UNSDG 2030)(UN, 2018). In Goal 1 (No Poverty) and Goal 2 (Zero Hunger), fishing has a significant role in achieving their targets. Fishing, by creating jobs, can increase the income of the people and can help in eradicating extreme poverty and hunger. As explained, UWN pollution can impact on the fishing industry by affecting fish productivity, changing their migration pattern and depression. This can result in a significant negative socio-economic impact on the society and threatens both job and food security. Furthermore, as described in Chapter 1, UWN should be considered as a type of pollution and proper actions should be taken to prevent and significantly reduce it. This is exactly what is considered in Goal 14 (Life below the water) in its first target, which is about preventing and significantly reducing all kinds of pollution by 2025.

There is also an indirect relation between Goal 13 (Climate action) and UWN pollution. Goal 13 is one of the most important goals of the UNSDGs. Due to the concentration of Co2 in the atmosphere, many issues have been introduced to human life. One of the most important ones is ocean acidification (Diaz-Pulido et al., 2012). Specifically, the amount of low-frequency noise absorption by decreasing PH (increasing ocean acidity) is declining and by the end of the century, due to the increase in ocean acidification, anthropogenic sound absorption will decrease dramatically (Ilyina et al., 2010).On the other hand, the increase in ocean acidification results in the reduction of the biological sound in the sea. For example, Rossi et al., (2016) reveal that ocean acidification effects not only the reduction of sound of snapping shrimp, but also reduces their number. In conclusion, ocean acidification reduces absorption of the low frequency and production of biological noise and, as a result, enhances UWN pollution.

As mentioned, UWN pollution is a new environmental issue for stakeholders and not everybody is aware of the issue and its consequences; moreover, in contrast to many other types of pollution, it is not a visible one. To make it visible, a scientific approach and proper data collection should be done and its negative externalities, especially in respect of business and economy should be properly visualized for the society and stakeholders. By this type of approach, proper drivers and motivation will be created to create legislation. The next step is elaborating the relationship between UWN and the UNSDGs, and its effect on sustainable development. This can help raise more attention to UWN pollution. In fact by extending the relationship between the UNSDGs and UWN pollution, the basis for legislating UWN will be established. As described, the UWN has direct connections with Goal 1 (No Poverty), Goal 2 (Zero Hunger), and especially Goal 14.1 (Life below the water), and has an indirect relation with Goal 13(Climate change), but further comprehensive study is required for the elaboration of more detailed links and relations.

2.3 Sources of underwater noise in commercial vessels

According to (Hildebrand, 2009), the sources of noise from commercial ships are:

- Propeller
- Propulsion machinery, and
- Hull design.

The 3 factors will be discussed in this section.

2.3.1 Propeller

Noise is a form of lost energy. So when noise is created, it usually means that energy could be saved through better maintenance or silencing equipment/redesign. The noise produced by propellers in terms of both intensity and spectral content has been considered important to warships and submarines to reduce the risk of being detected by the opponent (Vrijdag et al., 2010).More recently, it has become important for commercial vessels due to marine environmental issues. Analysis of the noise from ships demonstrates that their propulsion systems are a dominant source of UWN radiation at frequencies below 200 Hz (Ross, 1976; Arveson & Vendittis, 2000; Hildebrand, 2009).

There are five principal causes of noise propagation from the propeller:

1- The displacement of water by the propeller blade profile.

2- Due to the propeller rotating the pressure difference between the suction and the pressure surface of the propeller forms.

3- The flow over the surfaces of the propeller blades.

4- The variable wake introduced to the propeller creates fluctuation of the cavity volumes to the blades.

5- Sudden cavitation bubbles collapse.

The first three causes always exist whether the propeller is in cavitation condition or not. However, the last two depend on the cavitation phenomena (Carlton, 2012).

As a result, the propeller noise can be divided into two parts of:

1-Non-cavitation noise (More interest for the naval vessels such as anti-submarine frigates).

2-Cavitation noise (Designers try to increase the Cavitation inception Speed (CIS) (The lowest speed at which cavitation occurs) as much as possible).

Cavitation (broadband when bubbles collapse, but generally low frequency) and blade rate tonal (narrowband and also generally low frequency) sounds are a dominant source of underwater noise (Hildebrand, 2005; Hildebrand, 2009; IMO- MEPC, 2009). Although at low speed the machinery is the dominant noise, after reaching CIS the propeller propagation noise becomes the dominant factor (Ter Riet et al, 2003). By reducing the ship's speed to less than CIS, the noise propagation can mitigate properly. The CIS value for any particular warship is classified at about 15 knots. Meanwhile, several studies on propeller design were conducted to increase the CIS about 10 knots in commercial vessels by utilizing advanced propeller technology (Atlar et al., 2001; Ter Riet et al., 2003; van Terwisga et al, 2004).

2.3.1.1 Non-Cavitation noise

The noise propagation from the blade frequency and broadband noise are completely distinctive. Due to the position of the propeller, which is usually behind the ship, varying wake fields are introduced. The inflow turbulence which introduces to the propeller and various edge effects such as vortex shedding, and fluctuating shear stress to the propeller's blade are the main reasons for the broadband noise (Li and Hallander,2013). A different angle of flow encounter with the blade can cause a pulse to the blade relative to the propeller blade frequency. This unsteadiness is because of the variation in the wake field.

While in the broadband we should consider the turbulence that exists inside the inflow from the propeller, it is necessary to consider both inflow over the propeller and also the turbulence in the Wakefield in order to reduce the noise propagation (Atlar, et al., 2001).

2.3.1.2 Cavitation noise

Cavitation leads to performance demotion, noise generation, vibration, and material erosion (Gindroz & Billet, 1998). Cavitation is formed when the low pressure created by the propeller creates thousands of bubbles (IFAW, 2008; Hildebrand, 2009) and by the collapse of cavitation bubbles, shock waves introduced to the propeller and noise propagation (Carlton, J., 2012). Traditional cavitation not only produces noise but can damage propeller blades by creating accelerated erosion. The surface of the propeller blades is subjected to different pressure fields as shown in Figure 2.3. The first sign is called "orange peel effect" and causes them to shrink like the fruit's skin (Nolet, V.2017).

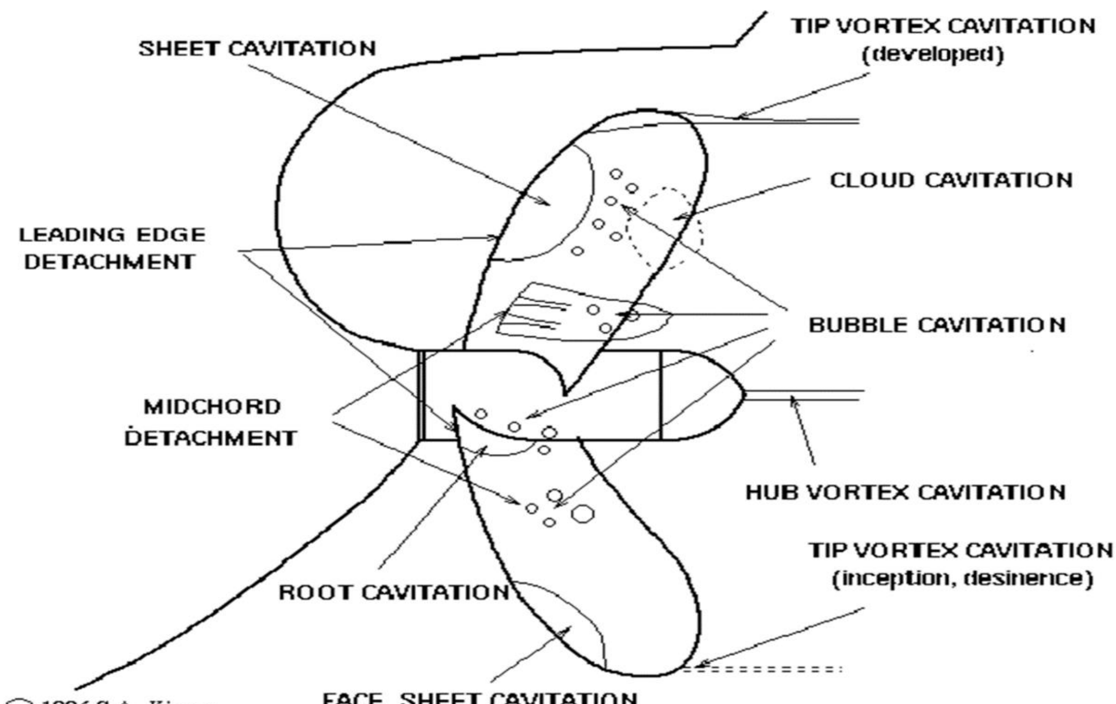


Fig 2.3. The propeller cavitation.
Source: (Kinnas, 1996)

The propeller cavitation can be formed during normal operations, and can peak at 50-150 Hz, but can extend at least up to 100,000 Hz (Veirs et al., 2016). The noise radiated by a cavitation propeller depends on the type of cavitation present at the particular operating condition. For example, back, face, hub and tip vortex cavitation types all have different noise signatures (Carlton, 2012). There is a great potential to reduce UWN radiation from commercial ships by reducing the cavitation.

2.3.1.3 What are the major aspects that influence the level of cavitation?

The propeller design and wake flow into the propeller are two major elements that effect the level of the cavitation (Renilson Marine Consulting Pty Ltd, 2009). Improvements in design, optimization in reducing load, and careful selection of the propeller characteristics (diameter, blade number, pitch, skew and sections) in respect of ships type, size and specifications can improve the mitigation of noise from the propeller (Nolet, 2017). The mean wake field, power, revolutions and ship's speed, determine the overall design, dimensions, and the local pitch of the propeller (Carlton, 2009). Off-design conditions impact on the ship propulsion system's behaviour. Resistance increase leads to higher engine loading, and reduces CIS (Vrijdag et al., 2010).
The blade area of the propeller is one of the functions of the cavitation. As the blade area increases, the cavitation will decrease. It is because of the increase of the thrust production by increase of the blade area. As a result, the differential pressure between the face (pressure side) and the back (suction side) will decrease. On the other hand, the greater blade area needs more torque to rotate propeller (Pty, R. M. C., 2009), which requires more power and the ship becomes less efficient. As a result, for optimal design of the propeller, it is necessary to trade-off between efficiency, cavitation and UWN radiation (Baudin et al.,2015). However, the relationship between cavitation, noise and efficiency is not completely clear and noise benefits from alternative technologies are still intellectual in most cases (ACCOBAMS, 2013).
The other effective factor on the cavitation performance of a propeller is the wake flow into it. The wake field in which the propeller operates is an important factor for propeller

design (Breslin & Andersen, 1996). There is potential to improve the wake flow in to the propeller by improving and optimizing design by using careful model testing (Lafeber et al.,2015) and also fitting appropriate appendages such as equalizing ducts, vortex or spoilers (Molland , 2011), which not only will reduce the noise propagation, but also improve the propulsion efficiency.

2.3.2 Noise from Machinery and Hull

2.3.2.1 Machinery

Besides the propeller noise, which propagates in water, noise from the machinery is another source of UWN (IMO, MEPC, 2014), and its main origins are from propulsion machinery and auxiliary engines (Prins et al., 2016). In the low speed before the CIS, the dominant noise propagation is from the machinery (Ligtelijn, 2007; Prins et al., 2016) with the frequency of <100 HZ (Nolet, 2017).

Most main engines of ocean-going vessels are heavy and low speed (70-120 rpm), 2-stroke engines that are directly connected to the single screw propeller shaft (conventional). In respect to their size and weight, resilient mounting is not suitable for them (IMO, MEPC, 2014) and they connect directly to the ship’s hull. Due to their vibration, the noise is transmitted from the ship’s hull to the water (Audoly et al., 2017). Other types of the ship's engines are 4-stroke engines with medium speed (500 rpm), which are connected to the propeller shaft by reduction gear (more common in CPP) or diesel generators which produce the required electric power of the ship (Andrew et al., 2002). Depending on the ship’s speed, the diesel generator noise can be the dominant noise in the ship with a low-speed propulsion engine. In contrast to 2-stroke, for the 4-stroke engines and the diesel generators, flexible coupling and resilient mounting can be considered, which can effect on reducing the vibration (Buzbuchi & Stan, 2010) and UWN radiation. This can be done with some form of elastic coupling between the engine and the gearbox and also use of vibration isolators for mounting of the generators to the foundations, reducing the radiated noise by 15 to 20 dB (Wright, 2008). Meanwhile, diesel-electric propulsion is a good option for the operational economy and also as an effective propulsion configuration for reducing underwater noise (BABICZ, 2015). Moreover, it has more freedom in location of the engine and using an isolation system to reduce the noise (Pty, R. M. C., 2009).

Proper design and selection of the proper machinery with respect to the type of ship in order to have less vibration can improve efficiency, maintenance cost, and UWN radiation. Furthermore, proper location (on the centre line) of the machinery and also optimization of the foundation should not be underestimated in reducing the vibration and UWN radiation (IMO-MEPC, 2017). Also, the proper maintenance of the machinery can affect fuel consumption, vibration, and UWN, accordingly (IMO-MEPC,2014).

Ship design plays a significant role in reducing UWN from machinery. The ballast and fuel tanks, cofferdams, and the double hull designed around the types of machinery can act as a buffer and reduce UWN propagation. Moreover, if the machinery manufacturers provide the information on the airborne sound levels and vibration produced by the machinery, better design, technology, and methods of mitigation can be utilized in reducing the noise and vibration (IMO-MEPC, 2017b). However, this information should be provided and be considered at the early design stage.

The type of fuel is one of the important factors that effects both emissions and UWN propagation. LNG and methanol engines, engines powered by fuel cells by low carbon fuels (e.g. natural gas and other low flashpoint fuels) and battery hybrid have much less vibration than the diesel types and mitigate both emissions and noise simultaneously (Tronstad et al., 2017). Since navy ships are very sensitive about the noise signature, considering the techniques that are used on them can be helpful in reducing UWN radiation. For example, according to Basten et, .al, (2010), using the active vibration control system that is used onboard navy ships can decay the underwater acoustic signature significantly.

2.3.2.2 Hull

Hull is another source of noise propagation. In comparison to the propeller and machinery, it does not have any significant role in producing noise. UWN radiation from the hull has two sources:

1- Vibration and noise of the types of machinery and rotating parts onboard the ship, which transfers to the ship's hull and radiates into the sea (has been explained in the section 2.3.2.1).

2- Various pressures which apply on the hull due to appearance and disappearance of the cavitation on the ship's hull (Prins et al., 2016).

The flow over the ship's hull is an important broadband noise-generating mechanism when the ship's speed increases (Hildebrand, 2005) and it produces more low-frequency noise (IMO-MEPC, 2014). Furthermore, a ship's hull can create the main source of the propeller cavitation, which is inhomogeneous flow and wake. A well-designed hull will reduce the resistance, resulting in less power required for the required speed (Tupper, 2013). Also, it provides more uniform and smooth inflow to the propeller and, as described before, it increases the efficiency, and reduces the vibration and noise.

With the improvement of the shipping industry and introduction of specialized vessels to enhance safety and provide better manoeuvrability, different requirements such as the bow thrusters, aft thrusters and fin stabilizers have been introduced. These requirements change the design of the ship's hull from traditional form to the new ship's hull shape, and innovation in ship design becomes a necessity. For example, bow thruster or stabilizer fins make the hollow on the ship's hull. This hollow shape in the hull not only affects the introduced wake and flow to the propeller, but also, due to turbulence during sea passage, can create more noise. By creating hatches for the hollows in the bow and/or aft thrusters and stabilizers fins and closing them during sailing, better interaction between the hull and the propeller will be formed and both efficiency and UWN radiation can be improved (Caizzi, 2018). Also, by applying a viscoelastic damping treatment to the hull and bulkheads in the tunnel of the bow thruster room, which is a major source of noise during operations, the noise can be mitigated dramatically (Babicz, 2015).

Chapter 3

3. Guidelines for the reduction of underwater noise from commercial vessels

Commercial vessels are one of the main sources of UWN radiation in oceans (IMO-MEPC, 2010). As mentioned in the previous chapters, propeller, machinery, and hull are the main sources of noise from commercial ships. In order to reduce the noise from commercial vessels, the following measures can be taken into account.

1) Ship design,

2) Operation and maintenance:

- Speed reduction
- Hull and propeller
- Convoy
- Rerouting

3) Combine different mitigation measures in a harmonized way.

3.1 Ship Design

Ship design and retrofit are source-based noise mitigation measures (DFO, 2017) and have the high potential for global and long-term effects in mitigation of UWN radiation; however, they can be applied gradually (IMO-MEPC, 2018). According to Spence and Fischer (2016), by only 1% increase in build cost, 10 dB noise reduction is possible, and this can reach 20–40dB by only ~10–15% increase (Southhall, 2005). Proper and correct design optimization in the early stage of design can not only mitigate the amount of the noise but is also a cost-effective measure and can prevent any further additional modification cost in future.

Retrofitting is the solution to the issue in respect of existing ships. The main purpose of retrofitting is usually changing the conventional propeller to one that is optimally designed to be quieter and more efficient for that ship (Spence and Fischer, 2016). For example, retrofitting the combination of the Contracted and Loaded Tip (CLT) propeller can be retrofit on an existing vessel without any modification to the ship's hull (Gaggero et al.,2016) or the forward-skewed nozzle propeller reduce the cavitation by increase the CIS (Southall and Scholik Schlomer, 2008), but optimization of the ship's hull and engine design / retrofitting is also an effective measure to reduce both emissions and UWN radiation. The best example in this respect is the world's largest container shipping company, MAERSK LINE, which in 2017 invested more than $100 million on a Radical Retrofit Program for 11 MAERSK G-class vessels to investigate and improve energy efficiency and GHG emissions performance. The retrofitting included replacing and using four-bladed propellers with boss cap fins to reduce cavitation, bulbous bow to reduce bow wave and wave breaking at the bow, and derating the main engines for slow steaming. The investigation shows that this retrofitting not only reduces the emissions but could also reduce 6 dB UWN in the low-Frequency band (8 - 100 Hz) and 8 dB in the high-frequency band (100 - 1000 Hz) in comparison with the pre-retrofitted vessel (Gassmann et al., 2017).

In the optimization of ship design, the following stages can be considered;

- Optimization of the propeller and its interaction with the ship's hull
- Machinery and Engine room design
- Computational and experimental modelling methods.

3.1.1 Optimization of the propeller and its interaction with the ship's hull

The main source of ship noise emission is cavitation. Meanwhile, hull formation can also affect the amount of cavitation (Nolet, 2017). In many cases, noise reducing propeller designs are available. However, due to technical or geometrical constraints such as ice strengthening propeller, and also effect on efficiency by reducing the cavitation (i.e. reduce pitch at the blade tips), they cannot always be utilized (IMO-MEPC, 2014).Trade-offs should always consider optimization of propeller design. It needs to optimize the propeller's efficiency while at the same time reducing the cavitation and the noise radiation. Meanwhile, this requires measurement methods to evaluate the effect of cavitation and other factors; however, with present methods, it is a very time consuming task. In this respect the SSPA in collaboration with other partners developed an acoustic method that will allow the model scale test to predict the risk of erosion and cavitation. It will also measure, evaluate and develop the equipment to determine whether the acoustic emission technique is useful in model scale and for full scale. By this method, different and large amounts of operation types can be considered and it is possible to map the result and make the best decision (SSPA, 2018 a).

Proper interaction between the ship's hull and the propeller can enhance both efficiency and mitigation of UWN propagation. The ship's hull, by providing a smooth and proper wake to the propeller, can improve the efficiency, and reduce the cavitation, and UWN. Designing and selecting a suitable propeller with respect to the type of ship and the ship's hull, which provides unique wake inflow, has a great effect on efficiency, and reduction of cavitation and noise. For example, the combination of the Contracted and Loaded Tip (CLT) propeller with higher block co-efficient vessels like tankers and bulk carriers can enhance propulsion efficiency and noise mitigation (Bertetta et al.,2012). Due to the nature of the operations of the ship and also to enhance manoeuvrability and safety, some changes to the ship's hull, such as hollows for aft and /or bow thrusters and stabilizer fins may be made, which will effect the proper flow to the propeller. These kinds of issues by innovation in design of the ship's hull, such as considering hatches for hollows on the hull (Caizzi, 2018), asymmetrical astern design to provide the homogeneous flow (can reduce the required power up to %9) (Breslin & Andersen ,1996), and utilizing different kinds of Propulsion Improving Devices (PIDs) such as pre-swirl, ducts, post-swirl fins and bulbs can be rectified (glomeep.imo.org).

3.1.2 Machinery and Engine room design

Machinery noise is the dominant noise at low speed. By mitigating the machinery noise, significant improvements can be obtained in reducing the UWN footprint (Audoly et al., 2013). The main sources of machinery noise are the main engine and the diesel generators. However, the diesel generator is dominant in machinery noise in ships with low-speed main engines (You, 2013).

The proper design of machinery can improve the efficiency, vibration and noise propagation. Although vibration of the engines depends on the number of cylinders, external factors such as exhaust gas pipe design, number of bends, interaction of other equipment such as scrubbers, SCR, and boiler are also effective (Babicz, 2015). As a result, it is necessary, at the time of design, to consider not only the vibration of all the machines individually, but also the interaction between them as a system, to mitigate the vibration and noise accordingly. For example, in electro-diesel engines which use as the main propulsion engines utilizing D.C frequency convertors creates noise but by removing the gearbox and making propellers run directly from the motors, the UWN will reduce significantly (Babicz, 2015). Another important factor in both emission and vibration of the engine is the type of the fuel. LNG, fuel cell and battery hybrid machinery can reduce both emissions and vibration (Tronstad et al., 2017).

The ship encounters various kinds of vibration during its operation with internal sources, such as main and auxiliary engines, and external sources, such as waves (Daifuku et al., 2016). The Anti-vibration characteristics are one of the most important design factors in the structure of ships, which will reduce the operation cost and improve both efficiency and UWN radiation. The optimization and reinforcement of the anti-vibration characteristics of the main engines and generators, such as optimization of the plate thickness of the ship's hull around the engine room (Kong et al., 2006) and the optimization of the size and shape of engine rooms, and location of the machinery in the engine room are effective measures in reducing the vibration and noise propagation (Daifuku et al., 2016). Furthermore, by improving the hull design and surrounding the machinery area with a fresh water tank (Kong et al., 2008), ballast tank, cofferdam, and double hull, resonance of the hull due to machinery vibration can be reduced and UWN propagation can be mitigated.

3.1.3 Computational modelling methods

Correct decisions at the early stage of designing can prevent any further cost burden to the shipowner. Considering and identifying the UWN radiation issue at the early stage of design is crucial. At the early design stage, considering the cost-effective and technically beneficial solutions can protect the re-design process and prevent any additional cost (SSPA, 2013). Hydrodynamic advice and expertise to evaluate the performance during the design period can help sustainable marine development. Without accurate and independent evaluation during the design stage, the shipping industry cannot develop energy efficient, safe (SSPA, 2018 b), and quieter vessels. Both experimental Fluid Dynamics (EFD) and computational Fluid Dynamics (CFD) models are used in ship design at various operating conditions and noise reduction before they are built (Wilson et al., 2001; Jasak, 2009; Gaggero et al., 2012). The EFD is done in a controlled laboratory environment (towing and cavitation tanks) and on scaled physical models (Bertetta et al.,2012). By simulating the ship's wake in the cavitation tunnel, the amount of cavitation for the full-scale ship can be evaluated. In this model all measurements are in accordance with the scale, to correspond to the full scale it is necessary to scale up the measured model (Li et al .,2018).
With increasing level of complexity and capability of the model, the CFD tools are used to predict UWN propagation. Types of computational models that may assist in reducing underwater noise are:

- Empirical /Semi-empirical methods; and
- Hybrid CFD method.

In this model, the sound radiation separates from its source. This will allow separating the flow solution from the acoustic analysis. By creating the turbulence model through the CFD technology, the wake flow field can be improved and the noise radiation is treated by acoustic analogy.

- Direct Numerical Simulation (DNS);

It is used to resolve the full spectrum of noise, and it requires strong CPU cores and high resolution which make it very expensive (Li et al., 2018).

- Statistical Energy Analysis (SEA) ;

It is used to identify and measure the high-frequency transmitted noise and vibration levels from machinery; and

- Boundary Element Method (BEM);

It is a numerical computational method for solving linear partial differential equations which have been formulated as integral equations and based on potential flow theory in which turbulence and viscosity effects are ignored (Li et al .,2018).

- Finite Element Analysis (FEA) ;

The low-frequency noise levels from the structure of the ship which are created by the fluctuating pressure of propeller and machinery can be measured and estimated by this analysis (IMO, 2014).

The CFD is able to model many phenomena and, since it does not need the physical requirements, is more cost-effective than EFD (Mason et al., 1998). Furthermore, it has a higher capacity and provides a larger amount of data by solving the simulation (Stern et al., 2006) in comparison to EFD, and has a significant role in both design and prediction of noise propagation. However, utilizing only CFD methods alone is not a reliable and proper solution. The combination of both CFD and EFD methods can have a greater potential for prediction and develop the improved design of the ship (SSPA, 2018 b).

3.2 Operation and maintenance

The main source of the UWN mitigation is from the ship design (i.e. hull form, propeller, the interaction of the hull and propeller, and machinery configuration), but the operational modifications and maintenance measures should not be underscored in reducing noise for both new and existing ships (IMO-MEPC,2014).

Ship's hull cleaning, polishing and cleaning of the propeller, and reducing the speed not only reduce the noise radiation but can also, simultaneously, mitigate emissions (IMO-MEPC, 2009). Moreover, rerouting (Nolet, 2017), and convoy (Williams et al., 2018) are other operational measures to reduce noise. Rerouting, slow steaming, and convoys have local effects (DFO, 2017) with high potential to mitigate noise in a short period of time; however, they may result in higher operation costs to shipping companies due to delays which their fleets encounter (IMO-MEPC, 2018).

3.2.1 Ships hull and propeller maintenance

Marine fouling can be formed on the ship's hull and the propeller after a period of time (Swain et al., 2007). It increases the ship's hull resistance, fuel consumption (Schultz et al., 2011) and operational cost (Stanley, 2016). Moreover, negative externalities such as introducing invasive species to the environment should be taken into account (De Poorter, 2010). Furthermore, the fouled ship's hull provides an uneven wake field to the propeller (Munk, 2006) and leads to cavitation and UWN radiation.

Propeller polishing can remove the marine fouling and reduce surface roughness and help in cavitation reduction. Furthermore, underwater hull cleaning maintains the smooth surface of the hull and the paint and will reduce the ship's resistance and the propeller load (IMO-MEPC, 2014). Hence, regular hull and propeller maintenance can improve efficiency and reduce UWN by up to 1- 2 dB (Baudin and Mumm, 2015).

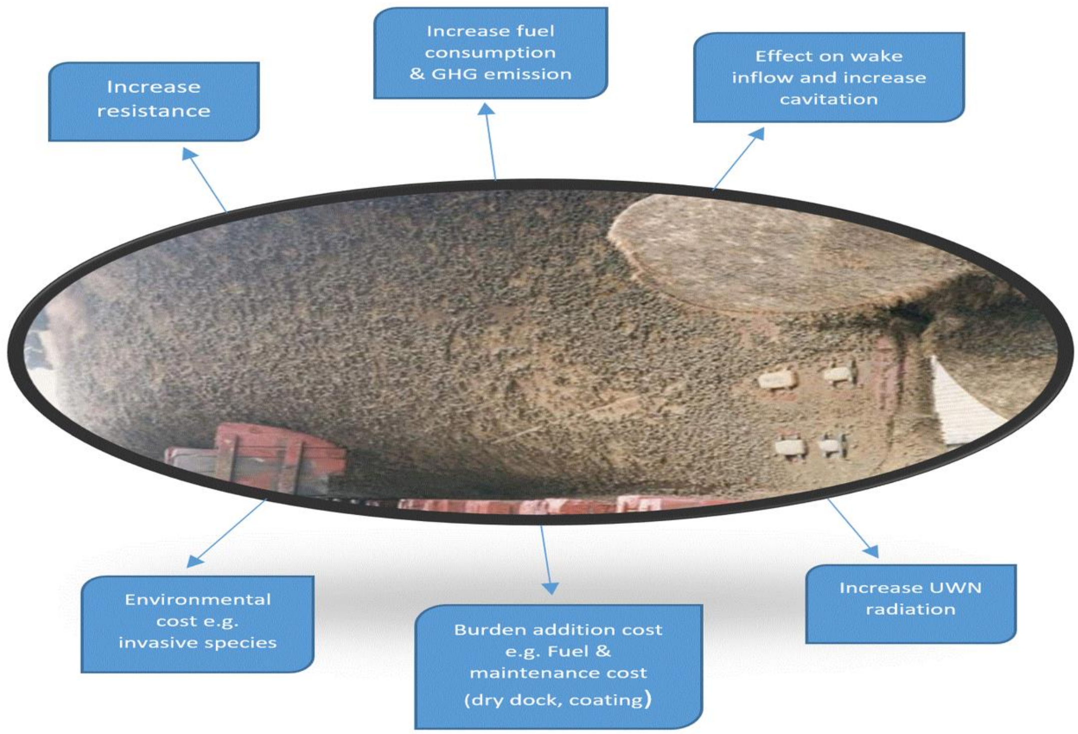


Fig 3.1. The ship's hull and propeller fouling effects.

3.2.2 Ship Speed

When re-routing shipping lanes are not possible, reducing vessel speed may be the only alternative method to mitigate UWN immediately (POV, 2017). Ships with higher speeds radiate more UWN at a higher intensity into the marine environment (Simard et al., 2016). As explained before, the main source of noise from commercial ships is cavitation and this occurs when the speed reaches CIS.

Reduction of speed has the immediate effect of reducing UWN radiation, especially if the speed reduction reaches less than CIS, its effect becomes more significant (IMO-MEPC, 2014). Although slow steaming reduces the noise level in the area, the duration of the noise propagation in the area increases, and needs the trade-off between travelling slower and spending more time in an area (McKenna et al., 2013).The mitigation effect from slow steaming is not equal between different ambient sound conditions, species, and vessel types (Pine et al.,2018). For example slow steaming is a very effective measure to reduce UWN for the FPP propeller, but it may not be effective for CPP (IMO-MEPC, 2014).

Many studies have been conducted in the relation of slow steaming and mitigation of UWN. Veirs et al., (2016) announced that in many ships, a 1knot reduction in speed leads to a 1dB reduction in broadband source level. Furthermore, according to the ECHO program of the Port of Vancouver (2018), the mean source level (broadband MSL) reductions, in decibels (dB) per knot (dB/Knot), for different types of ships in Haro Strait are provided as follows:

2.8 dB/knot reduction for bulk/general cargo ships

1.5 dB/knot reduction for container ships

1.7 dB/knot reduction for passenger/cruise ships

2.6 dB/knot reduction for tankers

1.6 dB/knot reduction for vehicle carriers

From the above figures, it is found that the largest reduction in UWN radiation per knot belongs to vessels with higher Block coefficient (Cb) such as Bulk/General Cargo vessels (2.8 dB/knot), and tankers (2.6 dB/Knot). However, it should be considered that there is not a linear relationship between source level noise emission and vessel speed, and these figures are the mean or average value (MacGillivray and Li, 2018). Since UWN is the function of many other factors such as machinery types, loading condition, and draft, these figures can vary from ship to ship, even in the same types.

3.2.3 Re-routing

Rerouting, such as the Ports of Oakland and San Francisco (WWF-Canada, 2013), and the Boston Traffic Separation Scheme (BTSS) (Hatch et al.,2008) and creating the prohibited area for navigation in vulnerable ecosystem areas like approaches to the Ports of Oakland and San Francisco (WWF-Canada, 2013), can reduce the impact of the shipping noise on marine life (Nolet , 2017) and provide an immediate acoustic benefit. However, it may also result in higher operating costs (IMO-MEPC,2018).

The main aim of rerouting is to protect marine life. Hence, the presence of the vulnerable species in the relevant area should be confirmed by taking such an action (Nolet, 2017). The more concentrated species in the area, the easier it is for ships to reduce the level of received noise by rerouting. Meanwhile, if the species is placed very close to the shipping lane (e.g, 100m), the received noise level can be dramatically decreased simply by moving the lane 20-100 m. However, if the distance of the species is larger (e.g, 1 nm), the lane should be shifted 800-2000m for a 3dB reduction (DOF, 2017).
Moreover, any rerouting without reduction of the source level is only causing a reduction in UWN pollution in the interested area; however, the area to which the route shifted encounters an increase in UWN pollution (if other variables are considered the same as before) (Williams et al.,2018). So to achieve the proper result, it is necessary to consider other mitigation measures to combine with the rerouting in order to reduce the source level of the noise simultaneously.

3.2.4 Convoy

Another method to protect the vulnerable marine species in the contingency areas and ports entrance is the convoy. It is a type of ship traffic control (Audoly et al.,2017). By this method, the spatiotemporal sound mitigation can be achieved by modification of the speed and time of transit of inbound and outbound vessels (Williams et al., 2018).
This method requires accurate planning, logistic support and collaboration of many stakeholders. Types of the vessels, port activities, traffic density, and capability of the port are effective in the level of success. Furthermore, speed limit , number of ships per convoy, timing of convoys (number per day, duration, times of day), and distribution of ships in a convoy (e.g., single-file or in parallel “lines”) are other important factors that can affect the degree of success (DFO,2017). Since the convoy requires the reduction of the ship speed (faster ships should reduce their speed and for container and cruise ship may become less than their CIS), the source level of the noise on each ship decreases and also the silent period of time in the area will increase. However, the

received level of the noise for the species will be increased during the passage of the convoy.

3.3 Combine different mitigation measures in a harmonized way

A harmonized combination of different mitigation measures (design and operational measures) can enhance the decay of UWN propagation. However, each individual and combination of measures, depending on the situation (noise is the function of many factors), may have different results (Williams et al., 2018). These combinations can be done in design or operational individually or mixed with each other. For example, a combination of Mewis duct and CLT propeller in a vessel are both in design/retrofit aspects. While the combination of slow steaming and changing the ship's propeller is a combination of design and operational aspects.

Meanwhile, in order to incentivize ship-owners and other stakeholders, it is important to combine the measures in such a manner that can improve fuel consumption and noise reduction simultaneously (IMO-MEPC, 2014). The Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) are important measures to improve the efficiency of the vessels. Meanwhile, some measures have the capacity to improve efficiency and reduce UWN radiation simultaneously. In the following section, some measures based on the SEEMP which can improve efficiency and UWN will be reviewed.

3.3.1 Just in time

This measure involves optimization of speed based on early communication with the next port on berth availability in order to arrive in ample time. If requires speed reduction, fuel consumption will be reduced. Moreover, in accordance with the ECHO, 2018 and other research, the reduction of speed in different types of the ships can lead to mitigation of UWN, accordingly.

3.3.2 Optimised Ship Handling

- Optimum trim (Operating at optimum trim for specified draft and speed).
- Optimum ballast (Ballasting for optimum trim and steering conditions).

Ships are designed for specific speed and load conditions. Not many ships can have the same state and load for all operations. Variable loading of the ship, altering the propeller depth from its design, is effective in the inception of cavitation, which is the main source of UWN radiation (Ross, 1976). Ballast ships are usually not in their loaded condition. Consequently, the propellers are much closer to the surface and not immersed properly and their tip becomes closer to the surface. The lower pressure due to less hydrostatic head causes more cavitation and noise propagation (Ligtelijn et al., 2014). Furthermore, the ship in ballast condition has more astern trim than its designed trim in full load condition. As a result, the wake field to the propeller will completely change and more cavitation for a vessel in ballast condition will have occurred (Lee, et al., 2009). These conditions are often seen in tankers or bulk carriers due to the nature of their business. Optimum trim and ballast condition not only helps in optimizing fuel consumption but will also reduce noise propagation. However, the relationship of these factors to noise propagation requires further study and, during the design period, the trade-off should be considered to settle the issue.

3.3.3 Optimum propeller and propeller inflow

As described in section 2, after reaching CIS, the propeller becomes the main source of noise propagation. The cavitation noise from the propeller is the dominant noise (10 dB above machinery and other noises) (Wittekind, 2008) of the propeller after its signing (Ligtelijn, 2007). By reducing the cavitation of the propeller, a significant amount of success will be achieved in the mitigation of UWN pollution. Although there are some techniques to promote CIS and delay the cavitation at higher speeds like navy ships and research vessels, it is not in favour of the commercial vessels because the efficiency of the propeller is affected (Brännström, 1995).

Wake in Flow is another main reason for cavitation formation. Each ship experiences varying inflow known as the wake. By retrofitting improved propeller designs and/or PIDs such as Schneekluth Wake Equalizing Duct (W.E.D), the Mewis Duct (MD), fins, not only is it possible to improve the efficiency, but also the cavitation will decrease and the noise propagation can be mitigated.

3.3.4 Hull and propeller cleaning and maintenance

After a period of time, due to the weakness of the coating, marine organisms can stick to the ship's hull and the propeller (Swain et al. 2007). The accumulation of biofouling on a ship's hull can increase drag, fuel consumption (Schultz et al. 2011) exhaust emissions, operational costs (Stanley et al., 2016), and reduce the inflow velocity to the propeller (Munk,2006).The most common method to control biofouling is through the application of fouling control coatings (Swain, 2010), but also mechanical hull cleaning through in–water is another approach to help in reducing the fouling on the ship's hull (Hunsucker et al, 2018). Hull cleaning is a viable method to reduce biofouling (Tribou, 2010). Hull cleaning reduces the turbulence between the hull and fluid around it, and decreases the loss of propulsion power (Veritas & DNV, 2015). In addition, by supplying smooth wake to the propeller, it reduces cavitation and mitigates UWN radiation (IMO-MEPC, 2014).

In addition, propeller polishing also removes marine fouling, reduces roughness on the propeller and reduces cavitation (IMO- MEPC, 2014), and UWN (Atlar et al., 2002; Mutton et al., 2005). According to Mutton et al., (2006), by applying anti-fouling on the propeller during measurements in a cavitation tunnel, the noise significantly reduced at some loaded for some frequencies.

Moreover, some individual ships have higher noise propagation than expected levels for given type, size, class, and speed (Veirs et al., 2016), which may be related to propeller damage. Meanwhile, by periodical hull and propeller cleaning, any damage can be assessed and, by rectifying the problem, mitigation of UWN pollution can be achieved (McKenna et al., 2013). According to Baudin et al., (2015) hull and ship maintenance every 6 months can lead to a reduction in UWN radiation of 1-2 dB.

Chapter 4

4. Development of the methodology for the trade-off between noise, emission, and fuel cost

4.1 The research methodology

As is shown in Figure 1.2 (can be reviewed in the next page), after a holistic approach and systematic literature review in respect of the topic, the collected data was classified into two groups, quantitative and qualitative. In both groups, a comparative analysis was conducted. The qualitative analysis was used for conceptual aspects and the quantitative one used for developing the modelling, Monte-Carlo Simulations, MCDM (MADM algorithms), TOPSIS, and the sensitivity analysis. The details of the analysis will be elaborated in section 5.2.1.

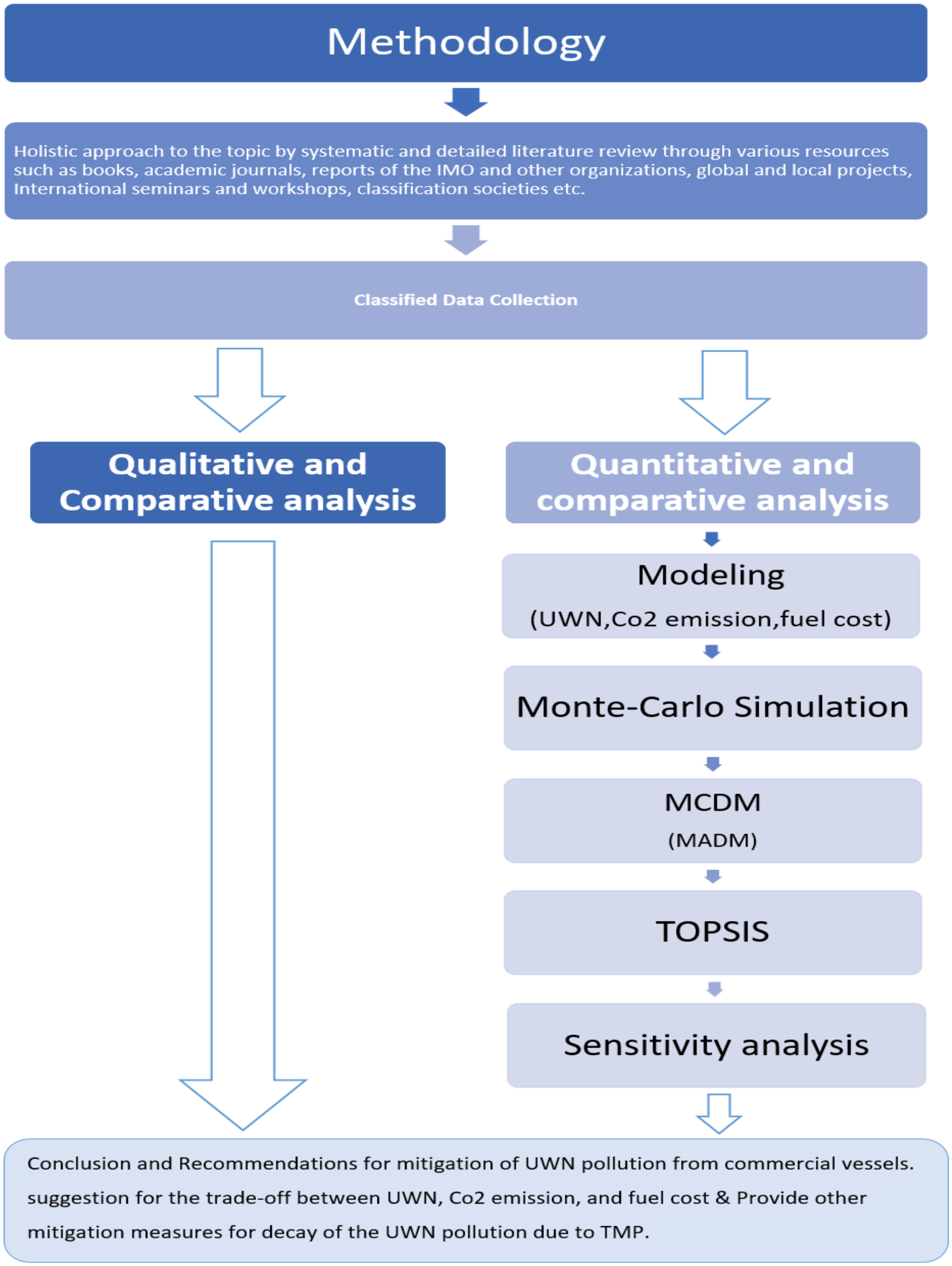


Fig 1.2.The research methodology

4.1.1 The modelling

4.1.1.1 The modeling inputs (variable and constant) and assumptions.

In this study, four scenarios were considered and, for each of them, modelling was created. The accuracy of a model depends on the data input. The variable and constant inputs and assumptions for the modelling of the study are as follows;

Variable input:

- Variable alternatives speed (v);
- Duration of transit;
- SFOC of tugs and tankers;
- Fuel consumption of each alternatives during transit the study area, and
- Monthly fuel consumption.

Constant inputs:

- Coefficient factor (C_{ϑ}) for calculating the MSL of tankers ($C_{\vartheta} = 7.625$);
- The source level at reference speed (v_{ref});
- Carbon Factor (CF) for Co2 emission (3.11);
- Number of visiting tankers in Port of Vancouver (34 vessels), and
- Fuel price (580 $/m.t).

Assumptions:

- Tugs fuel consumption with ±% 10 assumption in Monte- Carlo-Simulations;
- Constant MSL of 191 dB for the tug in scenarios with the constant UWN radiation for tugs;
- Constant MSL of 199.7 dB for the towing tug in all scenarios;
- The MSL of the tug in scenarios with variable UWN radiation considered to be changed 3.4 dB per 1 Knot;
- Average MSL of the 187.2 dB for13.68 knots speed for tankers;
- ±% 10 assumption in yearly increase of fuel cost;

- ±% 10 margins assumed for fuel cost in 2020 ($580/m.t) in Monte- Carlo-Simulations to calculate the monthly fuel cost, and
- ±% 10 margins in monthly fuel consumption in Monte- Carlo-Simulations to calculate the monthly fuel cost.

Moreover, for sensitivity analysis (C_i^* value maximization) the margins considered in the decision defined part for MADM matrix data are as follows:

- %$\pm$10 margin for Co2 emission and total fuel oil price;
- ± 2 dB for the MSL of UWN radiation, and
- All attribute weights considered be change betwwen 0.1 and 0.9.

4.1.1.2 Monopole Source Level (MSL) of the tankers and the tugs

The main goal of the modelling is to make a trade-off among the 3 pillars of sustainable development in respect of the TMP, which are the environmental (UWN and Co2 emission), economic (fuel cost), and social (side effects of UWN pollution, Co2 emission, and fuel cost)). In this respect, data was collected and four scenarios were developed and improved. The scenarios will be elaborated further in section 5.2.1. To create the models, it was necessary to collect data in respect of the minimum Monopole Source Level (MSL) (a source level that considers the effect of the sea surface and seabed on sound propagation) of Aframax type tankers and tugs. After the literature review and study, the average speed of the tankers for the studied area (Haro Strait) was considered to be 13.68 knots, with average MSL of the 187.2 dB(MacGillivray and Li, 2018).

To calculate the change in source level with speed, Ross's classical power law model (Ross 1976) was used as shown in Equation 1.

$$SL\text{-}\ \ SL_{ref} = C_{\vartheta}\ \times 10\ log_{10}\left(\frac{\vartheta}{\vartheta_{ref}}\right) \qquad (1)$$

SL : is the source level at speed ϑ through water;

$SL_{\ ref}$: is the source level at some reference speed $v_{\ ref}$, and

C_ϑ : is a coefficient corresponding to the slope of the curve.

The C_ϑ (Speed coefficients) can be calculated from the Equation 2:

$$C_\vartheta = \frac{SL2 - SL1}{10\ LOG_{10}\left(\vartheta_2/\vartheta_1\right)} \qquad (2)$$

In accordance with MacGillivray and Li (2018), the C_ϑ (MSL) for a tanker is 7.625. From the Equation 1 and 2 the source level of the tanker with the change of speed can be achieved from the Equation 3 as follows:

$$SL - SL_{ref} = 7.625 \times 10 \log\left(\frac{\vartheta}{\vartheta_{ref}}\right) \qquad (3)$$

In respect to the tugs noise radiation, after the literature review, many different results have been achieved. The results were completely different and there was not any consensus about the amount of UWN radiation. While some studies like MacGillivray and Li, (2018) reported that the noise propagation from the tug is almost constant (191 dB) in different speeds, in JASC0 (2014) different noise levels of 161,171.3,189 dB (3.4 dB per 1 Knot speed increase) were revealed for 4, 7.5, and 12 knots, respectively. Moreover, 199.7 dB was announced for the full power of the sample tug.

In this respect, in scenarios in which the tug's speed is considered to be changed, the tugs MSL is calculated for different speeds of 13.68, 10.5, and 7 knots and for towing alternative (4 knots), and the MSL of the tug that is engaged in towing is considered to be 199.7 dB. Meanwhile, the constant MSL of 191 dB is considered for the tugs in scenarios with constant UWN radiation.

To sum up the UWN radiation from the tankers and tugs and towing operation, equation 4 has been used as follows:

$$L = 10\ Log_{10}\left(\sum_{i=1}^{n} 10^{\left(L_i/10\right)}\right) \qquad (4)$$

4.1.1.3 The fuel consumption, fuel price, and Co2 emission

In respect of the tanker fuel consumption, Aframax ship data has been used; however, for the tug many kinds of literature was reviewed and communications conducted to achieve real figures but, unfortunately, no success could be achieved. Consequently, with respect to the author's experience and also reviewing the engine specs of different tugs, an assumption was made for the fuel consumption at different speeds and towing operation mode. Tables 4.1 and 4.2 show the fuel consumption of the tug and the tanker respectively.

Table 4.1. The assumed fuel consumption for tug in different alternative speed and towing condition.

Speed(Kts)	13.68	10.5	7	Tow(4 kts)
Fuel consp.accompany tug (ton/day)	6.48	4.968	3.3	2
Fuel consp.Towing tug (ton/hr)	0.35			

Table 4.2. The fuel consumption of the tanker in different alternative speed.

speed(kts)	7	10.5	13.68
Fuel consumption of the tanker (ton/day)	30.982245	45.02236	61.41828

Also, for a more accurate result in respect of tug's fuel consumption, a $\pm\%\ 10$ margin has been considered in the Monte-Carlo simulation.

With respect to the study area (16 nm), the duration of transit for different speed calculated and with reference to the SFOC of the tanker and the assumed tug, the fuel consumption for the transiting period was calculated as follows:

$$\text{Fuel consumption during transit the study area(ton)} = \text{SFOC}\left(\frac{\text{ton}}{\text{hr}}\right) \times \text{duration of transit (hr)} \quad (5)$$

The TMP will increase the tankers visiting the Port of Vancouver to around 34 vessels per month (Trans Mountain Pipeline ULC Kinder Morgan Canada Inc., 2017). As a result, the total amount of fuel consumption during transit for each alternative speed is multiplied by 34 and monthly fuel consumption calculated as follows;

$$\text{Monthly Fuel consumption(ton)} = \text{Fuel consumption during transit the study area (ton)} \times 34 \qquad (6)$$

For the calculation of the CO2 emission in accordance with the 2nd greenhouse study, the constant Carbon Factor (CF) of 3.11 was considered. By multiplying 3.11 by the monthly fuel consumption of each alternative speed, the total Co2 emission of the alternative speeds has been calculated.

$$\text{Monthly Co2 emission(ton)} = 3.11 \times \text{Monthly fuel consumption (ton)} \qquad (\mathbf{7})$$

With respect to the increase in demand for low Sulphur fuel due to the IMO Sulphur Cap 2020 (ICS, 2018), a ±% 10 yearly increase in price was considered from the present average value, which is $480/m.t (18.08.2018) (shipandbunker.com) and the price of fuel in 2020 (the Westridge Terminal commences its operation in 2020) been calculated at $580/m.t. Furthermore, to achieve a proper prediction in price, a ±% 10 margin was assumed in the Monte-Carlo simulations. By multiplying the monthly fuel consumption and price of the fuel in 2020 ($580/m.t), the total monthly fuel cost of each alternative speed has been achieved.

$$\text{Monthly fuel Cost (\$)} = \text{Monthly fuel consumption per month(ton)} \times \left(\frac{\$}{\text{ton}}\right) 580 \qquad (\mathbf{8})$$

4.1.2 The Multiple Criteria Decision Making (MCDM)

To have the proper decision making many factors such as identifying the problems, developing the preferences, evaluating the alternatives, and choosing the best alternative is necessary (Kleindorfer et al.,1993). Most decision making in the management, engineering, and operational aspects involves multiple potentially conflicting requirements (Yang, 2000). Multiple Criteria Decision Making (MCDM) is a technique to support decision makers who are encountering a number of conflicting alternatives to make an optimal decision (Tzeng & Huang 2011).

4.1.2.1 The Multiple Attribute Decision Making (MADM)

Most MCDM problems consist of goals, attribution weights, and alternatives. The MCDM is classified into two categories of Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM) (Tzeng & Huang 2011). In accordance with Dubois and Prade (1980), the MADM can be processed as follows:

- identify the nature of the problem;
- Create the hierarchy system for the evaluation of the system (Figure 4.2);
- Select the appropriate evaluation model;
- Obtain the relative weights and performance score of each attributes with respect to each alternative, and
- Determine the best alternative.

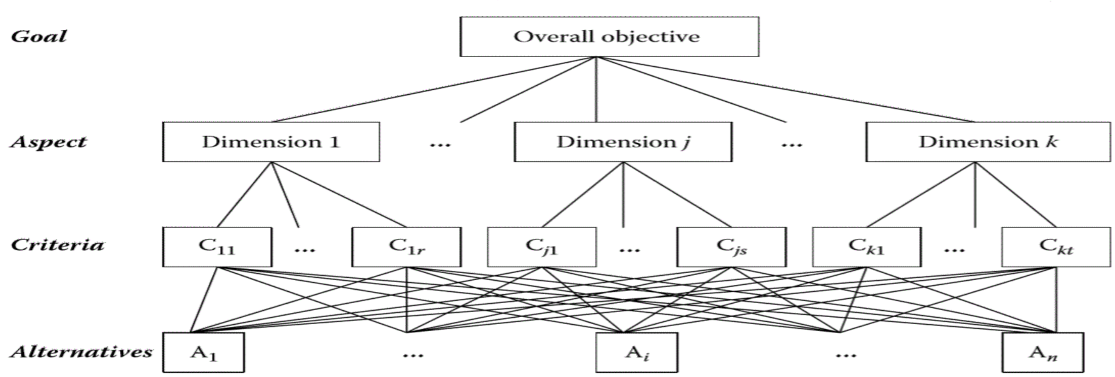


Fig 4. 1. Hierarchical system for MADM.
Source: (Tzeng & Huang 2011)

4.1.3 Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)

The TOPSIS was developed by Hwang and Yoon (1981) to identify the best alternative based on the solution which is nearest to the ideal solution and far away from the negative ideal solution (Zyoud & Fuchs-Hanusch, 2017). In the TOPSIS method, the best alternative is created from the different attribute values and can even consider invented alternatives.

The closeness (Similarity) (C_i^*) of each alternative is ranked based on its closeness to the ideal and the negative ideal alternatives simultaneously. The preferred order of alternatives is obtained by their rank on a descending order of those ratings (Tzeng & Huang 2011).

The procedure of TOPSIS is as follows:

Set of alternatives, $A = \{Ai \mid i = 1, \dots, n\}$, and a set of criteria $C = \{ Cj \mid j = 1, \dots, m\}$, where $X = \{Xij \mid i = 1, \dots, n\text{: } j = 1, \dots, m \}$ defines the set of performance ratings and $w = \{ Wj \mid j = 1, \dots , m \}$ is set of weights. The information table of TOPSIS can be shown as follows:

Alternatives	C_1	C_2	$\dots$	C_m
A_1	X_{11}	w_{12}	$\dots$	x_{1m}
A_2	w_{12}	w_{22}	$\dots$	x_{2m}
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
A_n	w_{n1}	$\dots$	...	x_{nm}
w	w_1	w_2	$\dots$	w_m

(Tzeng & Huang 2011).

4.1.4.1 TOPSIS calculation

Equation No9 transforms the attribute dimensions to non-dimensional attributes, which allows comparison across the attributes.

$$r_{ij}(x) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}, i = 1, \dots, n;\ j = 1, \dots, m. \quad (9)$$

Where x_{ij} is the value of the alternative i with respect to attribute j.

For the benefit criteria (larger is better), $r_{ij}(x) = (x_{ij} - x_j^-)/(x_j^* - x_j^-)$ where, $x_j^* = max_i\, x_{ij}$ And $x_j^- = min_i x_{ij}$ the x_j^* is the desired value and x_j^- is the worst level. For the cost criteria (the smaller value is better), $r_{ij}(x) = (x_j^- - x_{ij})/(x_j^- - x_j^*)$ and then the weighted normalized rating calculated by following equation;

$$\vartheta_{ij}(x) = w_j r_{ij}(x), i = 1, \dots, n;\ j = 1, \dots, m. \quad (10)$$

In the next step the positive ideal point (PIS) and the negative ideal point (NIS) are calculated as follow;

$$PIS = A^+ = \{v_1^+(X), v_2^+(x), \dots, v_j^+(x), \dots, v_m^+(x)\}$$
$$= \{(max_i v_{ij}(x) | j \in j_1), (min_i v_{ij} | j \in j_2) \mid i = 1, \dots, n\} \quad (11)$$

$$NIS = A^- = \{v_1^-(x), v_2^-(x), \dots, v_j^-(x), \dots, v_m^-(x)\}$$
$$= \{min_i v_{ij}(x) \big| j \in j_1), (max_i\, v_{ij}(x) | j \in j_2) | i = 1, \dots, n\}, \quad (12)$$

Where $j1$ and $j2$ are the benefit and the cost attributes, respectively.

For calculation the separation measures the following equations are used:

$$S_i^* = \sqrt{\sum_{j=1}^{m} [v_{ij}(x) - v_j^+(x)]^2}, \quad i = 1, \dots, n \quad (13)$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} [v_{ij}(x) - v_j^-(x)]^2}, i = 1, \dots, n \quad (14)$$

And the similarities to the PIS can be derived as:

$$C_i^* = S_i^* / (S_i^* + S_i^-), \quad i = 1, \dots, n, \quad (15)$$

Where 0< C_i^* <1 ; $i = 1,2, \ldots, n$

In the final step the preffered order can be obtained according to the similiarities to the (C_i^*) in descending order to choose the best alternatives (Zhang, 2004).

4.1.4 Sensitivity analysis

Using data achieved in TOPSIS techniques, a sensitivity analysis is conducted for each alternative. A maximization of their C_i^* value is done to find the optimum criteria of the alternatives. By applying the change factors to the attributes, the ranking of the alternatives can be changed. This makes a clear environment and helps optimize the Decision Support System (DSS).
In this study, in order to achieve a more accurate result and expand the probabilities in C_i^* value maximization criteria, in the decision defined part for MADM matrix data margins considered as follows:

- %$\pm$10 margin for Co2 emission and total fuel oil price;
- ± 2 dB for the MSL of UWN radiation;
- All attribute weights considered be change betwwen 0.1 and 0.9.

This expansion in C_i^* value maximization criteria creates a cleaner environment for decision makers and helps them with considering all probable possibilities to make the best decision.

Chapter 5

5. Case study: The Trans Mountain Project in Vancouver Port

5.1 Vancouver Port

Vancouver is located on the west coast of Canada, and it is Canada's largest port, and the 3rd largest tonnage port in North America, with the vision to be the most sustainable port in the world (POV, 2016). It extends from Roberts Bank and the Fraser River up to and including Burrard Inlet. According to the Port of Vancouver (2018) economic impact study, it has $200 billion in trade with 170 countries. The port activities contribute $11.9 billion, annually, to the Gross Domestic Product (GDP) and support 115,300 jobs in Canada, making a significant contribution to Canada's economic growth.
Figure 5.1 reveals the Vancouver port journey toward sustainability since 2008.

Fig 5.1. The Port of Vancouver Sustainability Journey.
Source: (Port of Vancouver.com)

Although the Port of Vancouver is one of the most pioneering ports in respect of marine environment preservation, it also has ambitious goals in Socio-economic aspects to achieve sustainability. In accordance with The Port of Vancouver economic impact study 2016, and as shown in Figure 5.2, the port is active in five business sectors: automobiles, breakbulk, bulk, container and cruise (Vancouverport.com).

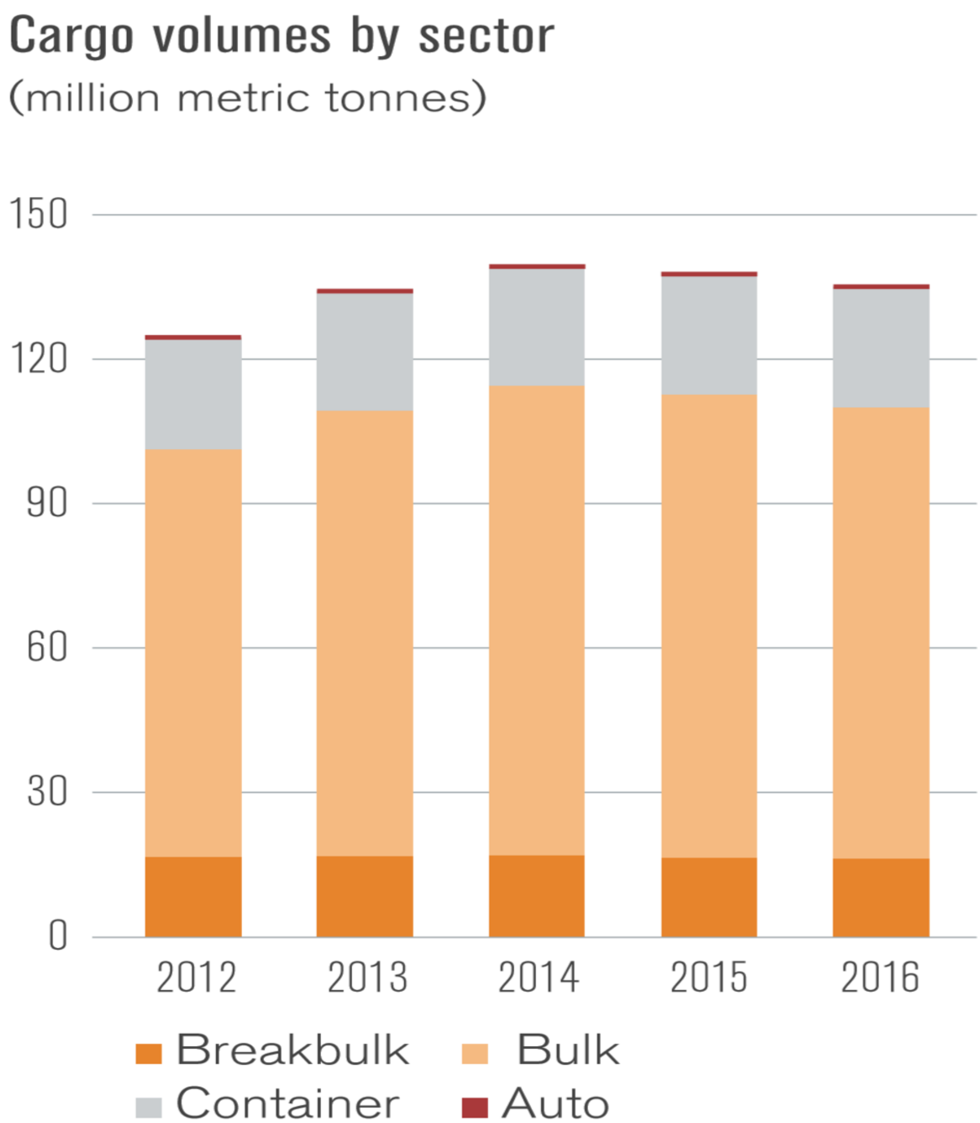


Fig 5. 2 Cargo Volume by Sector.
Source: (portvancouver.com)

Tankers have a significant role in the economic prosperity and development of the port. The largest tankers that are used to ship oil out of the Port of Vancouver are Aframax Tankers (80,000 – 120,000 DWT) (They can only load 80% of their capacity because of the draft and other restrictions).

Tankers currently represent about 2% of total ship traffic visiting the Port of Vancouver (out of 250 total vessels per month, about 5 are tankers). In September 2017, after a big debate and comprehensive study and consideration of the project impact on the community and the area, the Vancouver Fraser Port Authority approved a permit application from Kinder Morgan Canada to upgrade and expand the existing Westridge Marine Terminal in the Port of Vancouver, which is one component of Kinder Morgan's Trans Mountain Pipeline Expansion Project.

The project started in the fall of 2017 and is to be completed by spring 2020. This project will increase the number of tankers visiting the Port of Vancouver from around 5 to around 34 per month (Trans Mountain Pipeline ULC Kinder Morgan Canada Inc., 2017). Figure 5.3 shows the Kinder Morgan West ridge Marine Terminal Upgrade and Expansion Project Map.

Fig 5.3. Kinder Morgan West ridge Marine Terminal Upgrade and Expansion Project Map. Source: (https://www.portvancouver.com/development-and-permits/status-of-applications/kinder-morgan-westridge-marine-terminal-upgrade-and-expansion-project)

Increasing the traffic density, due to TMP, not only increases underwater noise, but air pollution and GHG emissions will be affected, accordingly. In accordance with the National Energy Board Report, (2016), it is estimated that by conducting the project annual marine combustion emissions will increase by 0.6 to 7 percent.

In addition, the passage route of the traffic in the area is through the marine mammal habitat of Southern Resident Killer Whales (SRKW) (DFO, 2011), which can jeopardize the recovery of the SRKW(DFO,2017). The unique SRKW is one of the most endangered marine mammal in the world (WWF-Canada, 2013). Somehow the NOAA fisheries listed SRKWs as endangered in 2005, and in 2015 named the SRKW a national species in the spotlight to focus efforts on recovering them (The SRKW are protected in Canadian waters under the Species at Risk Act)(NOAA, 2018).

Figure 5.4 shows the SRKW abundance from 1979 to 2017. As it demonstrates, the populations were abundant in the 1990s: however, they have declined dramatically since 2005. Today’s number is the lowest in the last 30 years, with only 76 individuals in 2017(DFO, 2017).

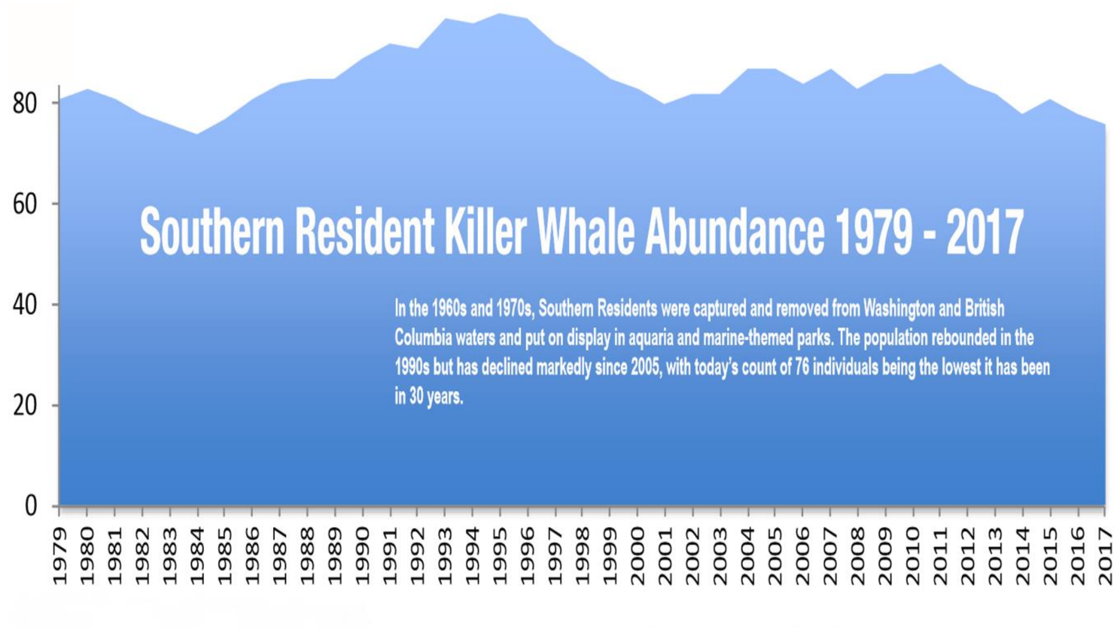


Fig 5. 4. Southern Resident Killer Whale Abundance 1979-2017.
Source : (www.westcoast.fisheries.noaa.gov)

According to Joy et al. (2017):

- Environmental contaminants;
- Availability of prey;
- Physical disturbance (ship collisions); and
- Acoustic disturbance (underwater noise) are the main threats to the SRKWs.

By conducting the TMP, the traffic density will grow by 11 percent, which will enhance the threats on the mammals. The effect of UWN pollution on marine mammals can be mitigated by one or a combination of protective actions. Examples include introducing innovative technologies and equipment, changes in the seasonal and hourly timing of noise production, operational measures such as slow steaming, and rerouting of noisy activities to keep the mammals clear of noisy activities (Richardson & WuÈ rsig, 1995) and also damping the noise between the source of the noise and the mammals. In addition, legislating in respect of underwater noise radiation can be a great step in mitigation of this issue

Although these are effective actions in reducing UWN pollution, this point of approach is single dimension thinking, which will not lead to sustainable development. In order to mitigate the negative impacts of the TMP, multi-dimensional thinking should follow. It is necessary to not only mitigate the threats individually in the area, but also to consider the trade-off between the sustainable development pillars (environment, social, and economical) in respect of the negative impacts of the TMP.

In the next section, the trade-off between Co2 emissions, UWN pollution, and fuel costs will be investigated in respect of TMP and also some technologies and mitigation measures which can help in reduction of the UWN pollution will be reviewed.

5.2 Mitigation measures for The Trans Mountain Project

With respect to the TMP and its effect in enhancing traffic density and its threat of endangering SKRW in the Haro Strait area, the following mitigation measures are suggested and will be discussed:

- Operational measures (Trade-off analysis in respect of TMP);
- Air Bubble curtain;
- Cold Ironing;
- Incentives.

5.2.1 Operational measures in the Haro Strait (Trade-off analysis in respect of TMP)

The majority of ocean-going vessels transiting to Vancouver and vice versa pass through the corridor which includes the Haro Strait. As Figure 5.5 shows, the Salish Sea is a high-density area in terms of SRKW population. The SRKW population is seen in all months of the year in the Haro Strait, but more commonly during the summer (May – September) (DFO, 2011). Due to high traffic density and UWN propagation from commercial vessels, the SRKWs communication is masked, their behavioural responses changed, and approximately 25 percent of all SRKWs have lost their foraging time (SMRU, 2014).

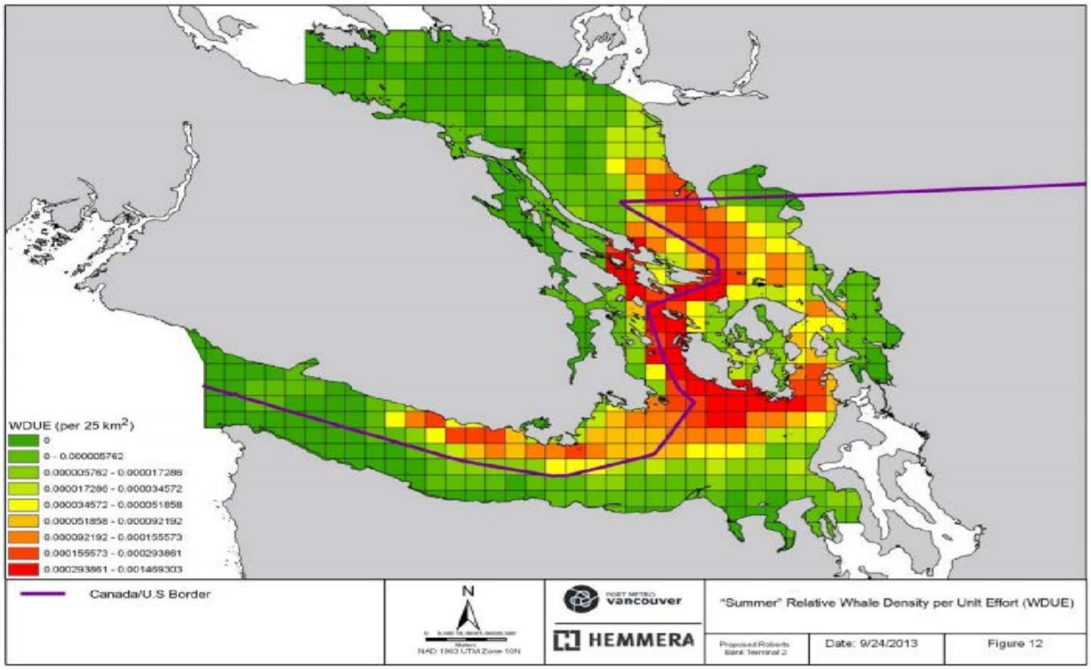


Fig 5. 5. Relative SRKW density in Salish Sea May-September.
Source : (Hemmera and SMRU,2014)

In 2017, under the ECHO program, a voluntary vessel slowdown was conducted. Due to the slowdown program, the vessels, while transiting the area (it is an important area for the feeding of SRKW (MacGillivray and Li, 2018)), radiated less UWN and introduced fewer exhaust emissions. However, the extent of the total mitigation depends on whether any actions will be taken to compensate for the lost time (MacGillivray and Li, 2018).

Figure 5.6 shows the area of the slowdown program (approximately 16 nautical miles), in which the vessels voluntarily reduced their speed up to 11 knots.

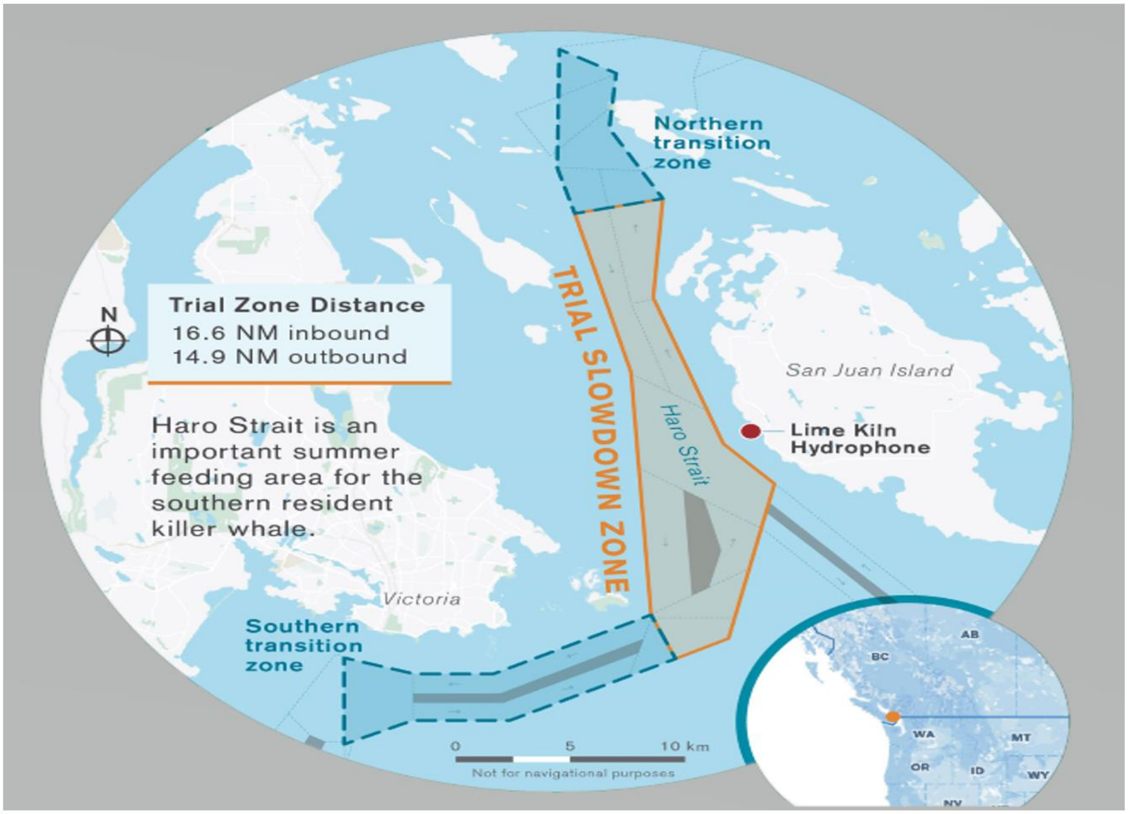


Fig 5. 6. Trial slow down Zone in Haro Strait.
Source: (Port of Vancouver.com)

As described in Chapter 3, in the ECHO program, the tankers achieved a 2.6 dB/knot reduction in UWN radiation by slow steaming. This can be a good operational measure in mitigation of the noise and Co2 emissions in the area.

Figures 5.7 and 5.8 show the inbound and outbound routes to the Westridge Terminal and the tug requirements before the commencement of the Westridge Terminal operation.

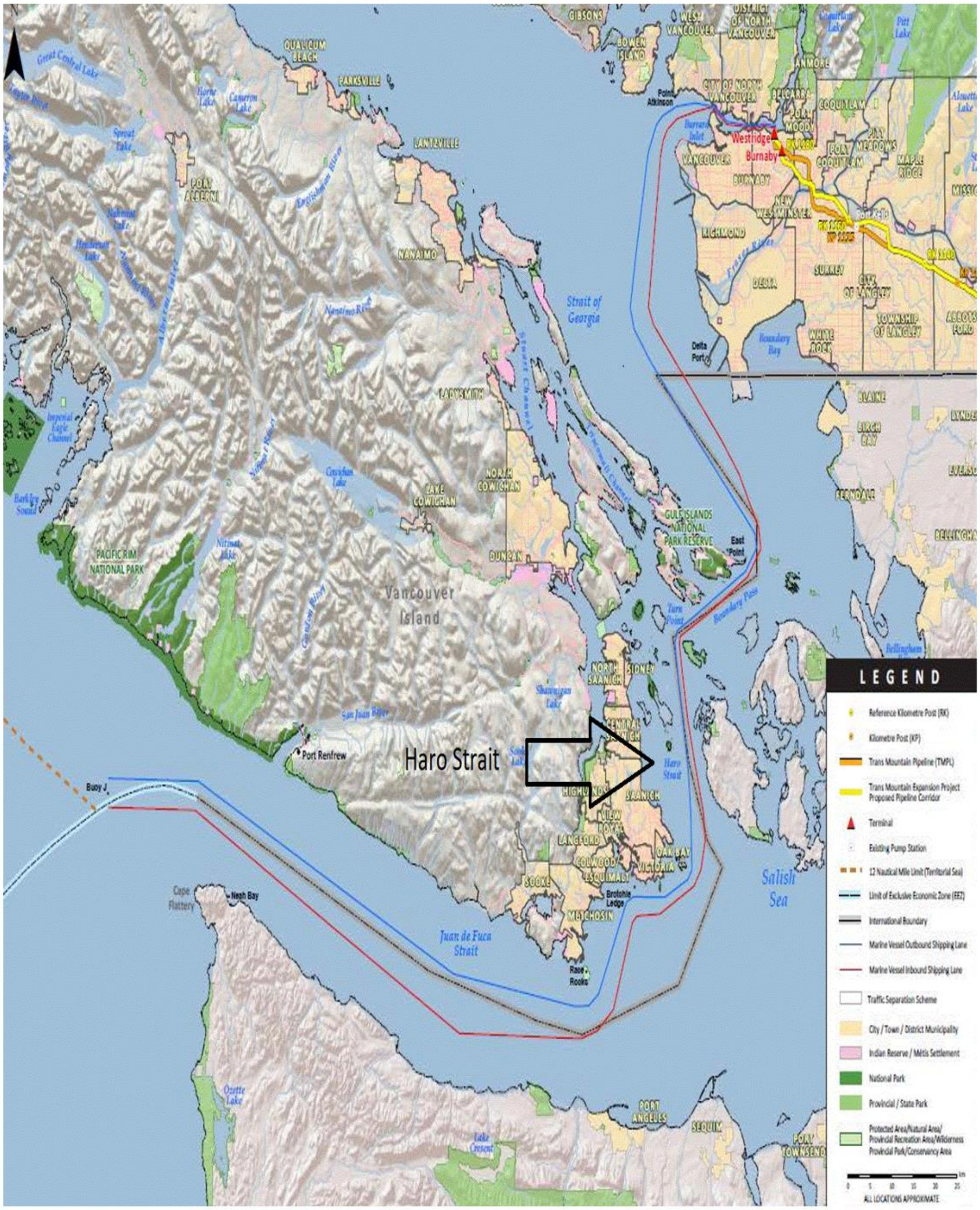


Fig 5. 7. Map of the TMP's Shipping Lanes (Inbound & Outbound).
Source: (Modified by author based on NEB b, 2016)

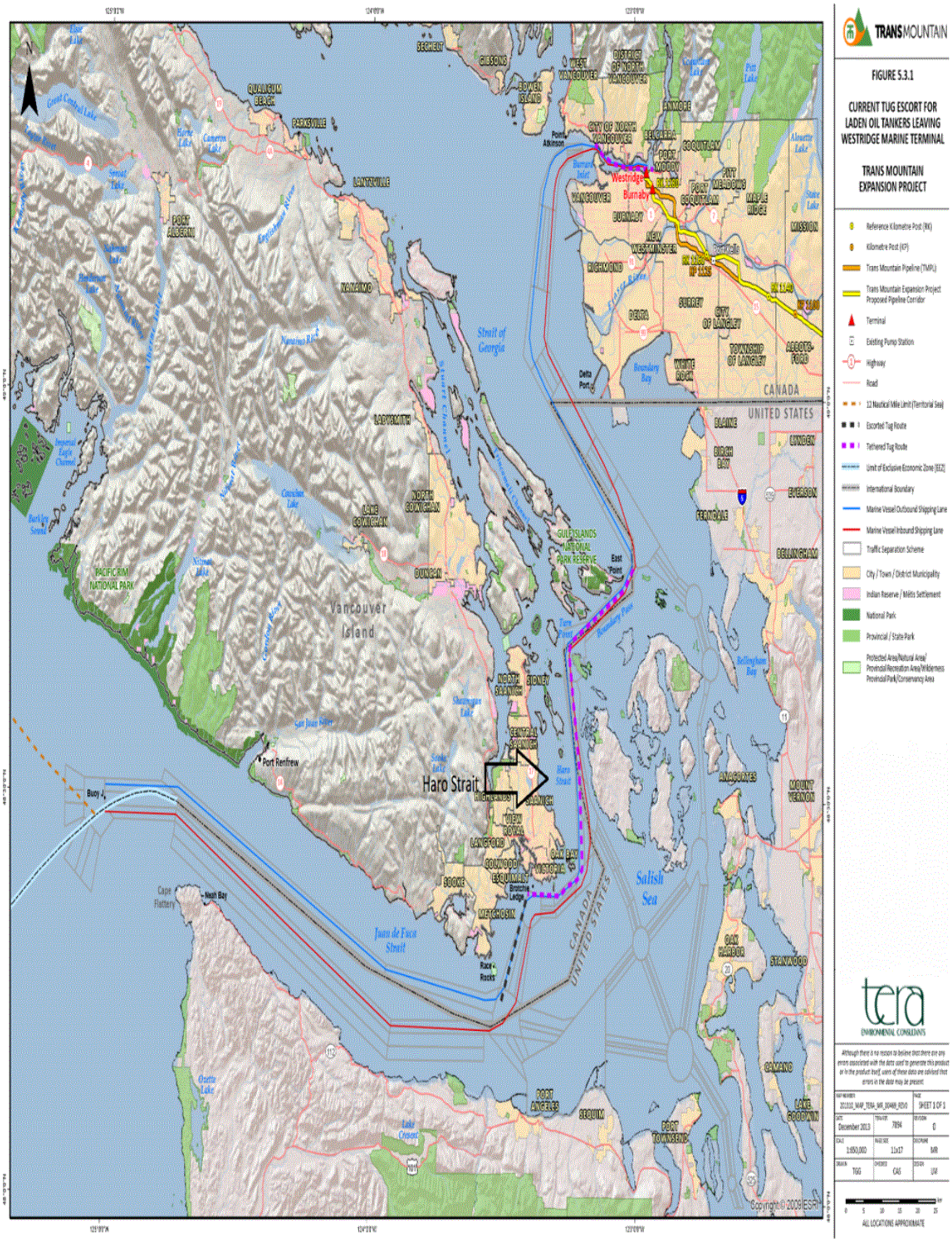


Fig 5. 8. The current tug escort plan for laden oil tankers leaving Westridge Marine Terminal. Source: (Modified by author based on Trans Mountain Expansion Project, 2013)

Meanwhile, as Figure 5.9 reveals, after commencing the operation of the Westridge Terminal in order to enhance the safety and reduce the likelihood of navigational incidents and any oil spill, the outbound tankers from the Terminal should be escorted by one tug to Buoy J where the Juan De Fuca Strait ends at the Pacific Ocean (NEB a, 2016).

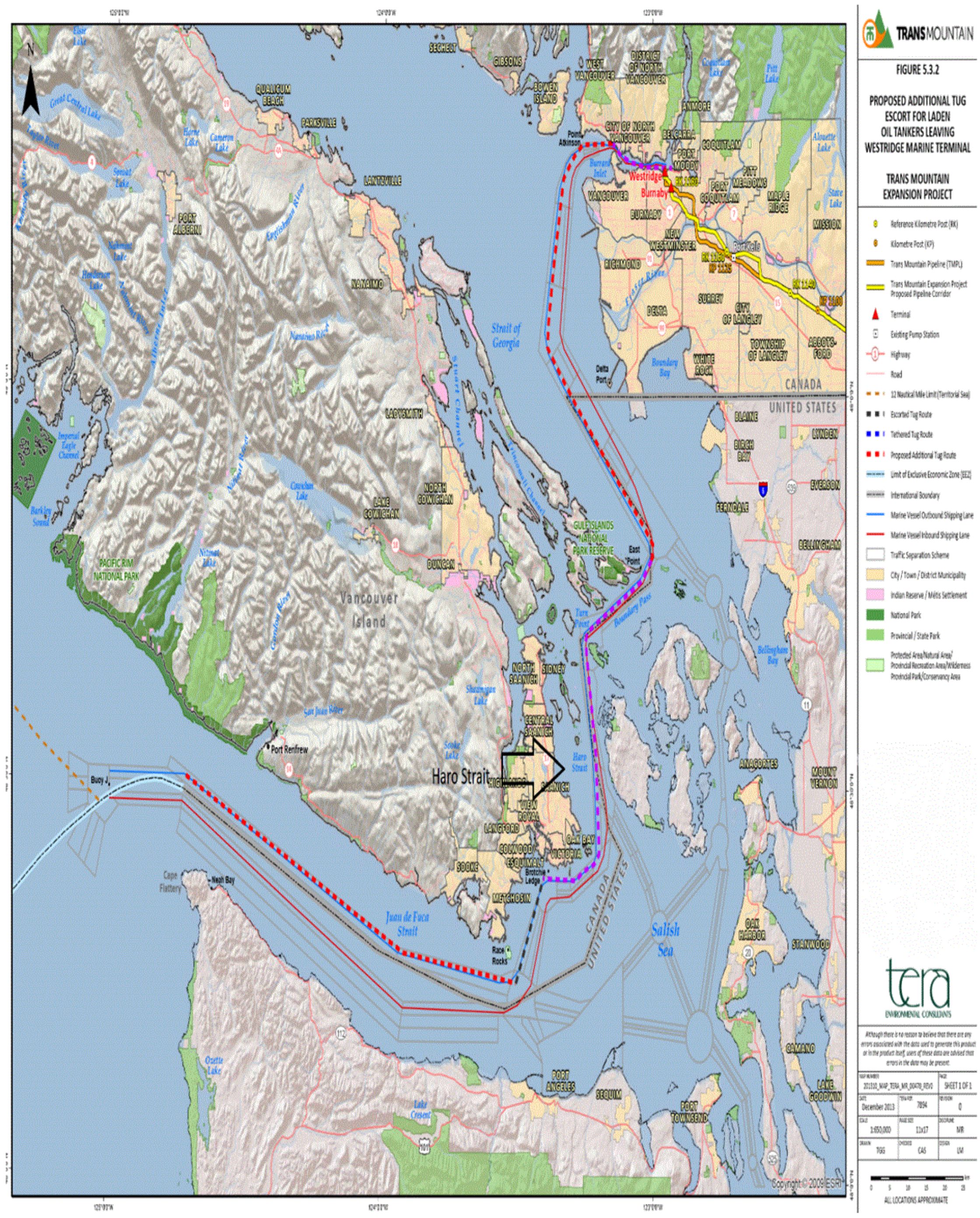


Fig 5. 9. The proposed tug escort plan for laden oil tankers leaving Westridge Marine Terminal. Source: (Modified by author based on Trans Mountain Expansion Project, 2013)

In this section, four scenarios are developed to trade-off between the different attributes (UWN pollution, Co2 emission, and the fuel cost) in order to help the decision makers to choose the best option to minimize the negative impacts of the TMP and support sustainable shipping in the area. In the scenarios, only the operational mode is considered and it is assumed that towing the tanker (with 4 knots speed) in the Haro Strait is safe and does not endanger the safety of navigation. The direct and indirect economic aspects of speed reduction to shipping companies, ports, and other stakeholders are not considered.

The formation of four scenarios is as follow:

1-Inbound tankers without tugs escorting, at speed of 13.68, 10.5, 7, and towing the tanker with two tugs (one tethered & the other accompanying) at 4 knots speed (The tugs noise radiation is assumed to remain constant with speed alteration).

2- Inbound tankers without tugs escorting, at speed of 13.68, 10.5, 7, and towing the tanker with two tugs (one tethered & the other accompanying) at 4 knots speed (The tugs noise radiation is assumed to change with speed alteration).

3-Outbound tankers, with one escorting tug and speed of 13.68, 10.5, 7, and towing the tanker with two tugs (one tethered & the other escorting) at 4 knots speed (The tugs noise radiation is assumed to remain constant with speed alteration).

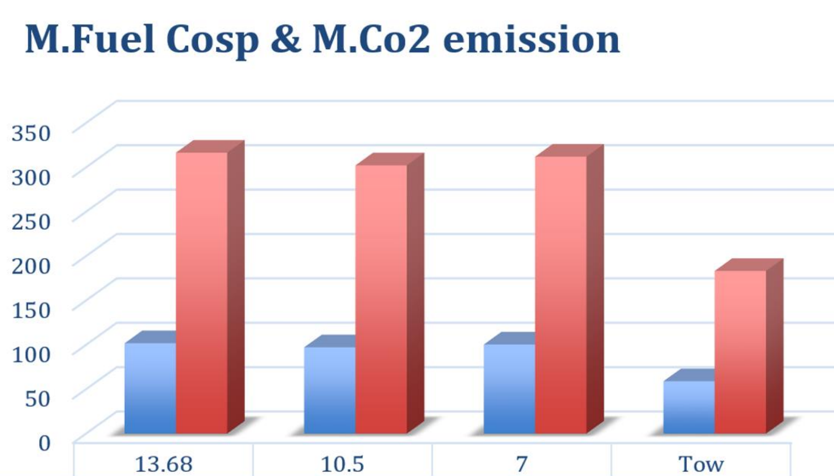
4- Outbound tankers with one escorting tug, at speed of 13.68, 10.5, 7, and towing the tanker with two tugs (one tethered & the other escorting) at 4 knots speed (The tugs noise radiation is assumed to change with speed alteration).

5.2.1.1 The Inbound tankers
(Tugs noise constant with speed alteration)

As explained before the inbound tankers are not escorted by any tugs. This scenario is based on the proceeding of the tankers with speed of 13.68, 10.5, 7 knots and also the tanker towed by a tug at 4 knots speed, while a tug escorts them for assistance in case of necessity. The fuel consumption of the tankers at the different speeds is the real data of an Aframax tanker; however, the tugs' fuel consumption is an assumption based on the literature review and the author's experience.

Referring to equation No5, the fuel consumption of the tanker and towing operation during transit of the studied area is calculated and, by equation Nos 6 and 7, the total monthly fuel consumption and Co2 emissions are calculated, respectively.

Figure 5.10 illustrates the monthly fuel consumption and Co2 emissions of the four alternatives.



	13.68	10.5	7	Tow
M.Fuel Cosp(ton)	101.76	97.19	100.32	58.93
M.Co2 emission(ton)	316.489	302.264	312.006	183.282

M.Fuel Cosp(ton) M.Co2 emission(ton)

Fig 5.10: Monthly fuel consumption and Co2 emission of the scenario 1.

With respect to the monthly fuel consumption and equation No8, the monthly fuel cost for each alternative is shown in Figure 5.11.

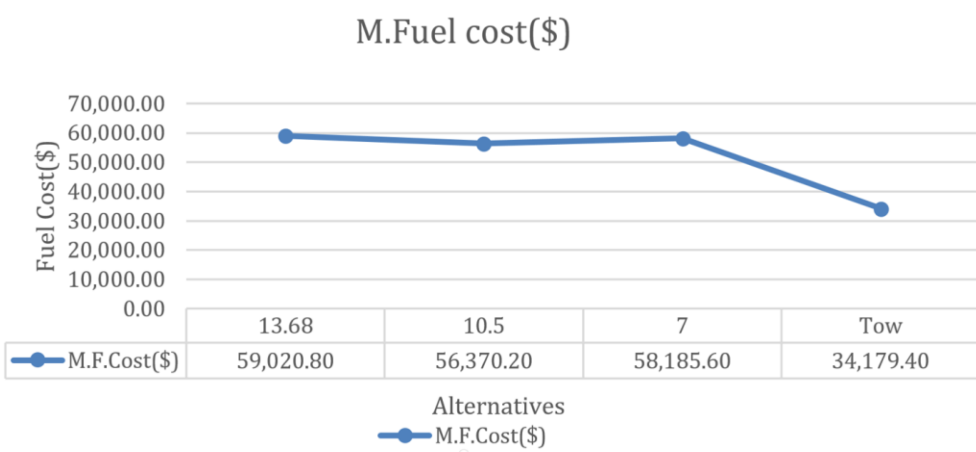


Fig 5.11. Total monthly fuel cost of scenario1.

For UWN radiation as described in Chapter 4, the MSL of the tanker at 13.68 knots speed is considered to be 187.2 dB and the MSL of other alternative speeds is calculated by equation No3. Meanwhile, the noise radiation from the accompanying tugs is considered constant with MSL of 191 dB and the tug engaged in towing is considered with MSL of 199.7 dB. The sum of the MSL of two tugs (accompany tug and towing tug) has been calculated by equation No4. Figure 5.12 shows the results.

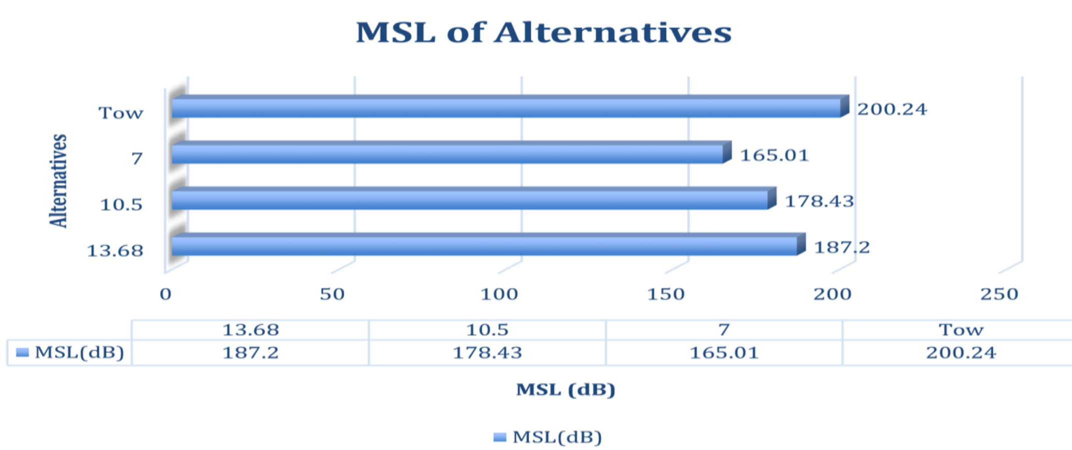
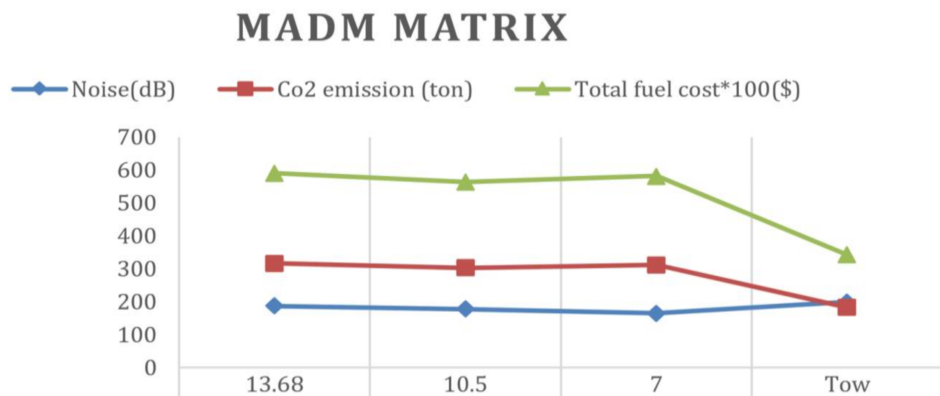


Fig 5.12. The MSL of different alternatives in scenario 1.

As Figure 5.13 illustrates with respect to the calculations and data achievement, the MADM matrix has been created for TOPSIS calculation.



	13.68	10.5	7	Tow
Noise(dB)	187.2	178.43	165.01	200.24
Co2 emission (ton)	316.489	302.26	312	183.28
Total fuel cost*100($)	590.208	563.702	581.856	341.794

Fig 5.13. The MADM matrix of scenario 1.

Calculations Tables and Monte-Carlo simulations graphs

The following are the tables of the MADM matrix data calculation. These calculations are based on the input data and assumptions, and refer to equations which were elaborated in chapter 4.

Tables 5.1 and 5.2 demonstrate the calculations of monthly fuel consumption and Co2 emissions, and monthly fuel cost, respectively. In Table 5.3, the alternative MSL calculations are revealed.

Table 5.1. Calculation of the alternatives' monthly fuel consumption and Co2 emission.

	TUG speed (kts)	Fuel Consp the tug (t/h)	Duration of transit (hr): (16nm/speed (kts))	F.Consp during transit for tug (ton): F.cosp(t/hr)*duration of transit(hr)	F.Consp for during transit for accompany and towing tank (ton): F.Consp during transit for towing tug (ton)+F.Consp during transit for accompany tug (ton)	Co2 Emission(ton) during transit: 3.11*F.Consp during Transit(ton)	Monthly F.Cosp(ton): 34*F.Cosp during Transit(ton)	Monthly Co2 Emission (ton): 3.11*F.Cosp in one month(ton)
Towing Tug	4	0.35	16/4=4	0.35*4=1.4	1.4+0.33=1.73	3.11*1.73=5.39	34*1.73=58.93	3.11*58.93=183.28
Accompany tug	4	0.083	16/4=4	0.083*4=0.33	/////	/////	/////	/////
	Tanker Speed (kts)	Fuel Consp the tanker(t/hr)	Duration of transit (hr): (16nm/speed (kts))	F.Cosp during Transit for tanker (ton): F.cosp(t/hr)*duration of transit(hr)	Co2 Emission(ton) during transit: 3.11*F.Consp during Transit(ton)	Monthly F.Cosp(ton): 34*F.Cosp during Transit(ton)	Monthly Co2 Emission (ton): 3.11*F.Cosp in one month(ton)	/////
	7	1.29	16/7=2.28	1.29*2.8=2.95	3.11*2.95=9.17	34*2.95=100.32	3.11*100.32=312	/////
	10.5	1.87	16/10.5=1.52	1.87*1.52=2.85	3.11*2.85=8.89	34*2.85=97.19	3.11*97.19=302.26	/////
	13.68	2.55	16/13.68=1.6	2.55*1.6=2.99	3.11*2.99=9.3	34*2.99=101.76	3.11*101.76=316.48	/////

Table 5.2. Calculation of the alternatives 'monthly fuel cost.

Alternatives	13.68	10.5	7	Tow
Monthly fuel cost($): Monthly fuel cosp(ton)*580($/ton)	101.76*580=59,020.8	97.79*580=56,370.2	100.32*580=58,185.6	58.93*580=34,179.4

Table 5.3. The alternatives MSLs calculations.

Calculation the MSL of alternatives		MSL(dB)
Equation for calculating the source level	SL=187.2+7.625×10 log⟦(ϑ/13.68)⟧	/////
13.68	SL=187.2+7.625×10 log⟦(13.68/13.68)⟧	187.2
10.5	SL=187.2+7.625×10 log ⟦(10.5/13.68)⟧	178.43
7	SL=187.2+7.625×10 log ⟦(7/13.68)⟧	165.01
Tow	Msl accompany tug=191dB, MSL towing tug=199.7 dB	/////
Equation for sum up two MSLs	$L = 10\ Log_{10}\left(\sum_{i=1}^{n} 10^{(L_i/10)} \right)$	/////
Sum up MSLs of Towing tug& accompany tug	$L = 10 * log_{10}(\sum 10^{(191/10)+(199.7/10)})$	200.24

With respect to the assumptions made in the Monte-Carlo simulation, forecasts are defined for the monthly fuel cost of the four alternatives and also the monthly Co2 emission of the towing alternative. The Monte-Carlo simulations were run (5000 trials). Figure 5.14 shows the monthly fuel cost of the 13.68 knots speed. As it shows, the mean and median of the monthly fuel cost are $59,036.22 and $58,990.18, respectively, with the standard deviation of 2,631.95. The calculated monthly fuel cost for 13.68 knots speed ($59,020.8) has the minimum certainty of 49.44% as shown in Figure 5.14.

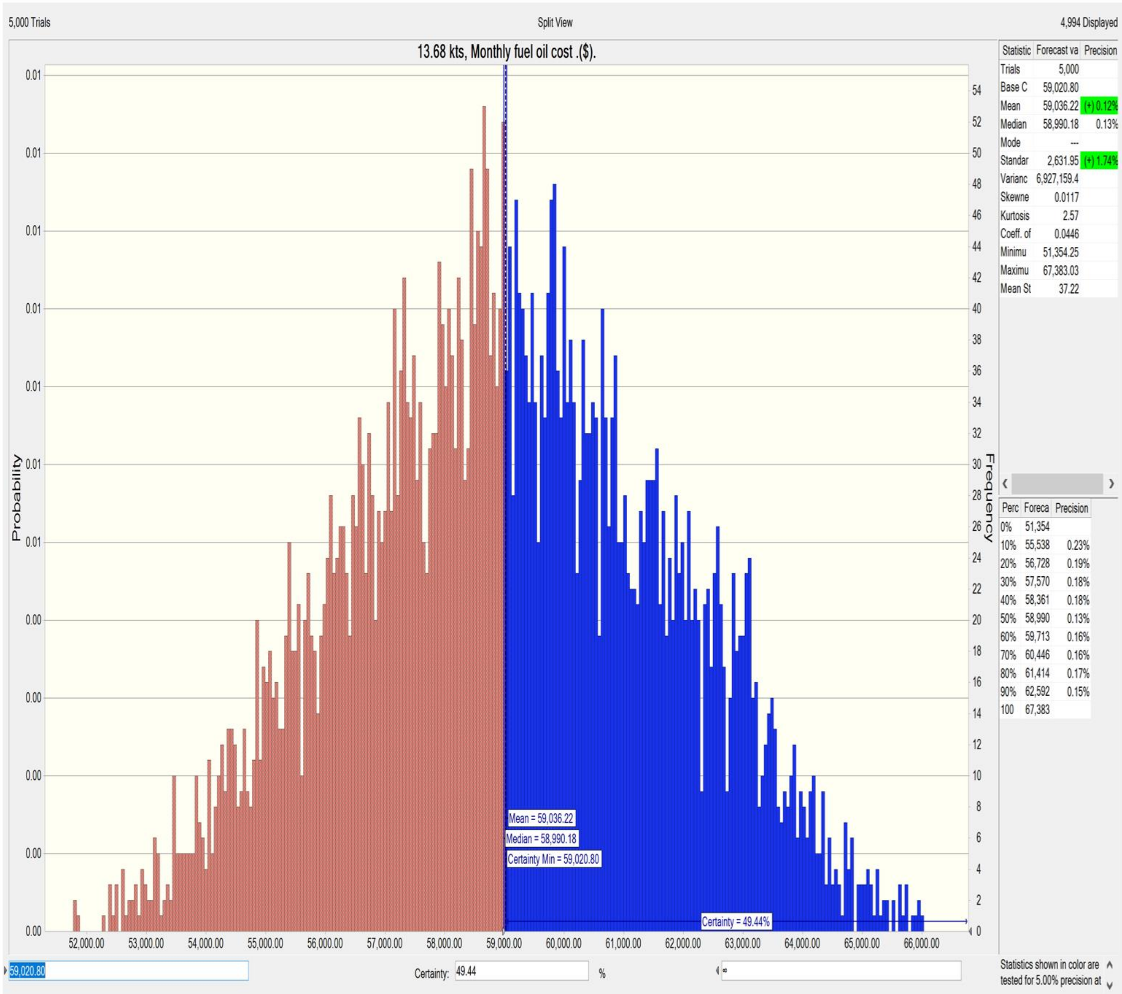


Fig 5.14. Monthly fuel consumption of the 13.68 knots speed.

Figure 5.15 illustrates the monthly fuel cost at 10.5 knots speed. As it reveals, the mean and median of the monthly fuel cost are $56,440.25 and $56,428.72, respectively, with the standard deviation of 2,510.05. The calculated monthly fuel cost for 10.5 knots speed ($56,370.20) has the minimum certainty of 50.89%, as shown in the Figure below.

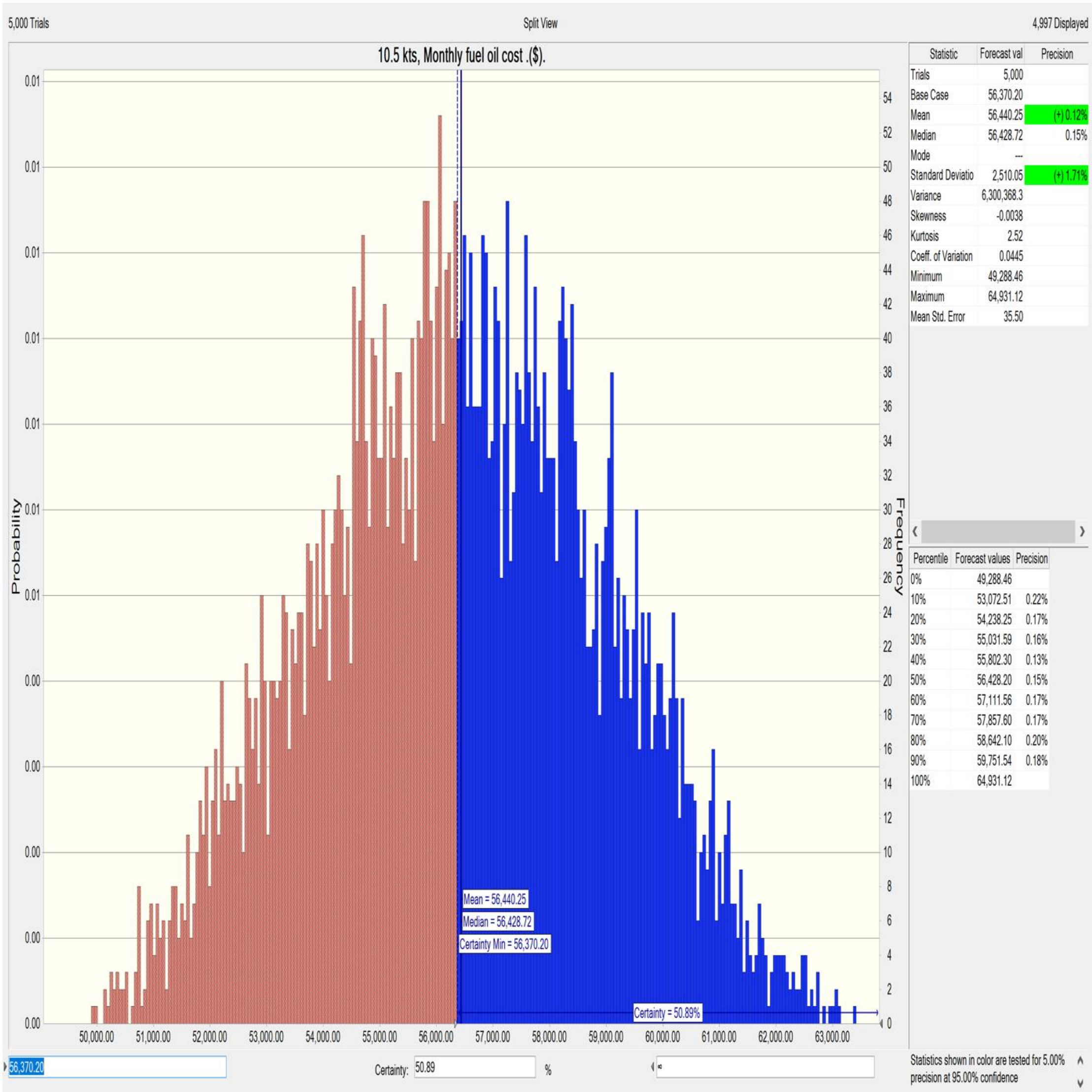
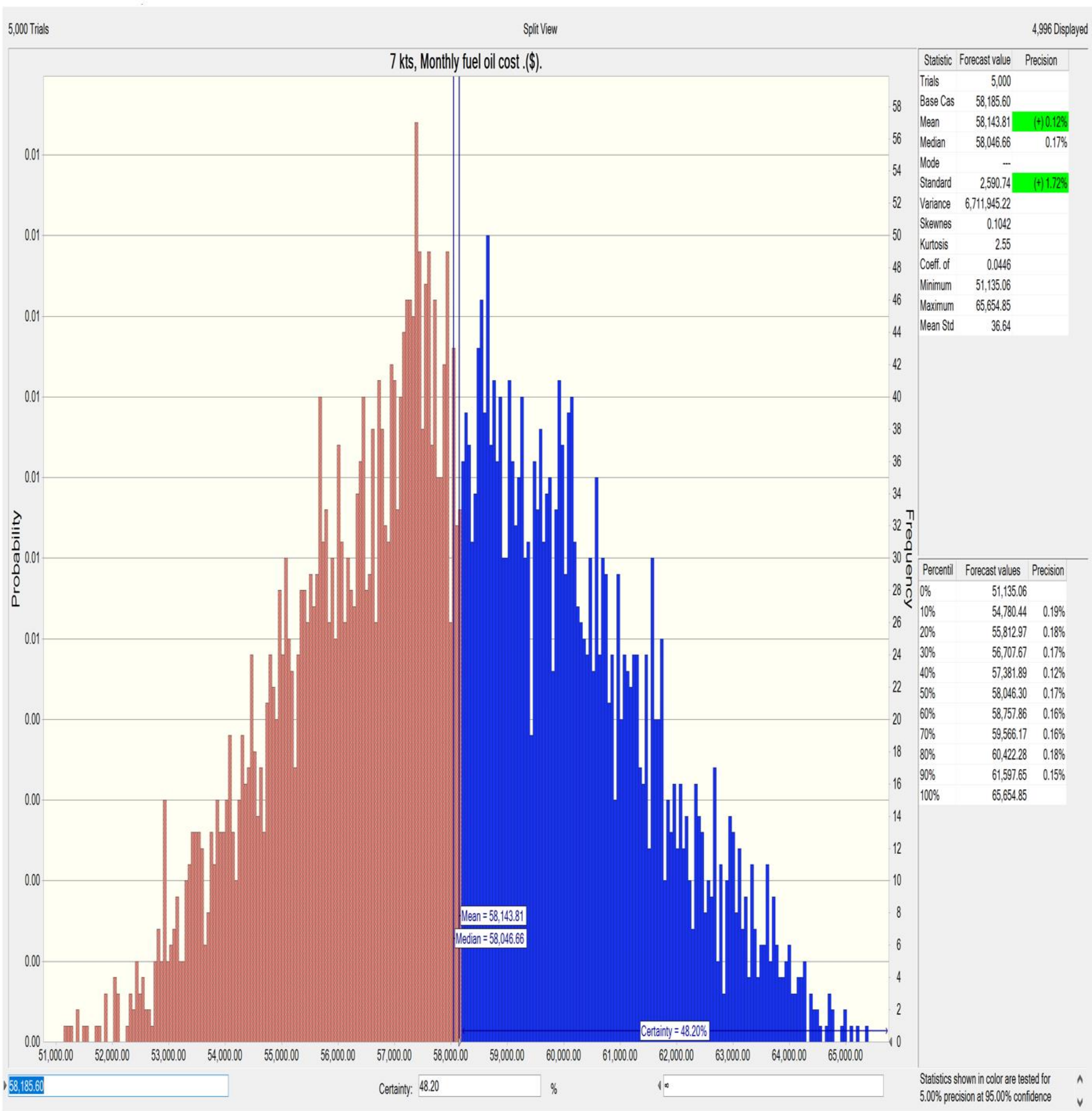


Fig 5.15. Monthly fuel consumption of the 10.5 knots speed.

Figure 5.16 reveals the monthly fuel cost at the 7 knots speed. As it reveals the mean and median of the monthly fuel cost are $58,143.81 and $58,046.66, respectively, with the standard deviation of 2,590.74. The calculated monthly fuel cost for 7 knots speed ($58,185.6) has the minimum certainty of 48.2%, as shown in the Figure below.



Statistic	Forecast value	Precision
Trials	5,000	
Base Cas	58,185.60	
Mean	58,143.81	(+) 0.12%
Median	58,046.66	0.17%
Mode	---	
Standard	2,590.74	(+) 1.72%
Variance	6,711,945.22	
Skewnes	0.1042	
Kurtosis	2.55	
Coeff. of	0.0446	
Minimum	51,135.06	
Maximum	65,654.85	
Mean Std	36.64	

Percentil	Forecast values	Precision
0%	51,135.06	
10%	54,780.44	0.19%
20%	55,812.97	0.18%
30%	56,707.67	0.17%
40%	57,381.89	0.12%
50%	58,046.30	0.17%
60%	58,757.86	0.16%
70%	59,566.17	0.16%
80%	60,422.28	0.18%
90%	61,597.65	0.15%
100%	65,654.85	

Fig 5.16. Monthly fuel consumption of the 7 knots speed.

The Figure 5.17 demonstrates the monthly fuel cost of the towing alternative. As it reveals, the mean and median of the monthly fuel cost are $34,177.59 and $34,176.5, respectively, with the standard deviation of 1,509.04. The calculated monthly fuel cost for the towing alternative ($34,179.4) has the minimum certainty of 49.91%, as shown in the Figure below.

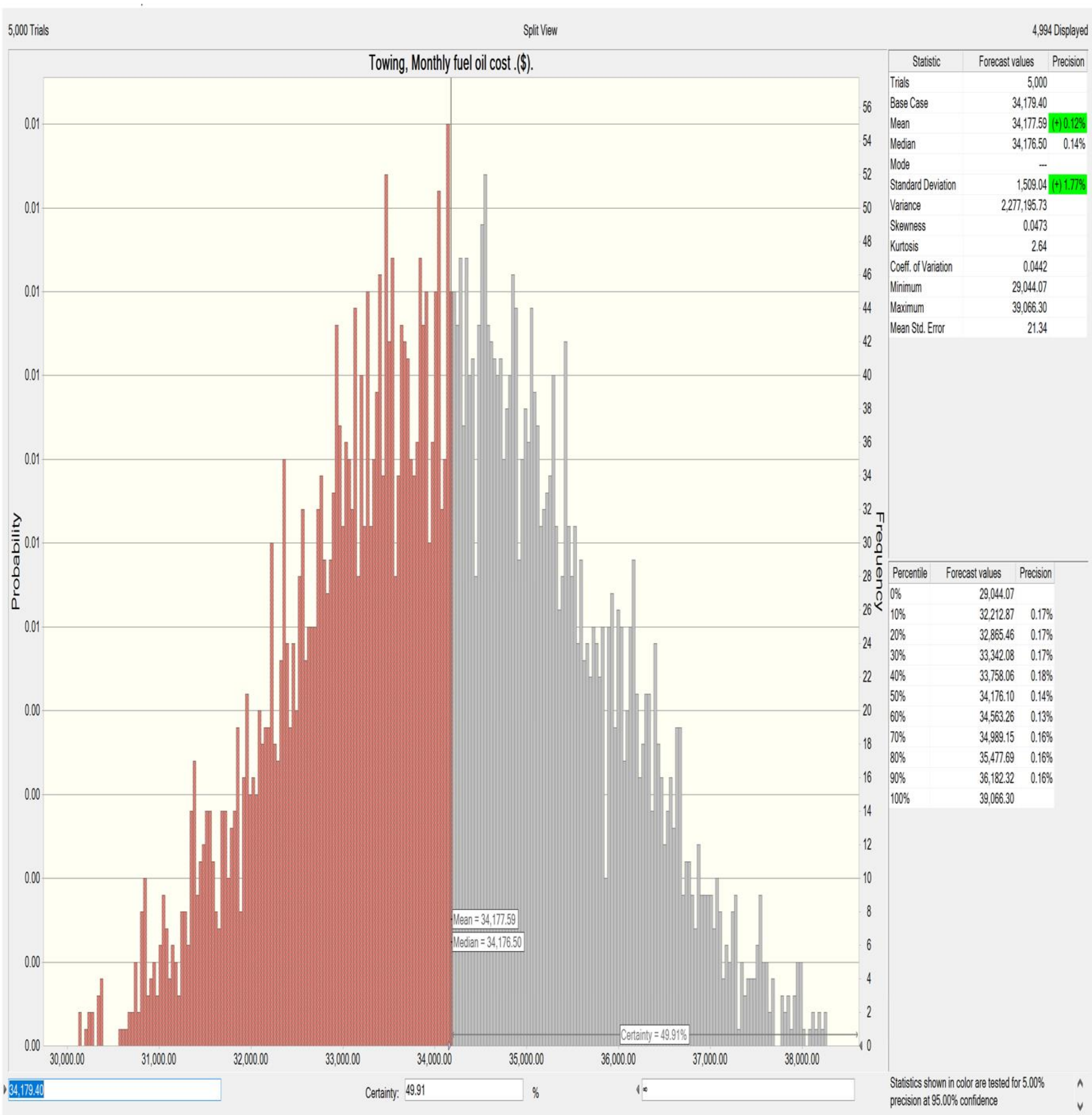


Fig 5.17. Monthly fuel consumption of the towing alternative.

Figure 5.18 reveals the monthly Co2 emission of the towing alternative. As it reveals, the mean and median of the monthly Co2 emissions are 183.32 (ton) and 183.26 (ton), respectively, with the standard deviation of 6.1. The calculated monthly Co2 emission for the towing alternative (183.28(ton)) has the minimum certainty of 49.87%, as shown in the Figure below.

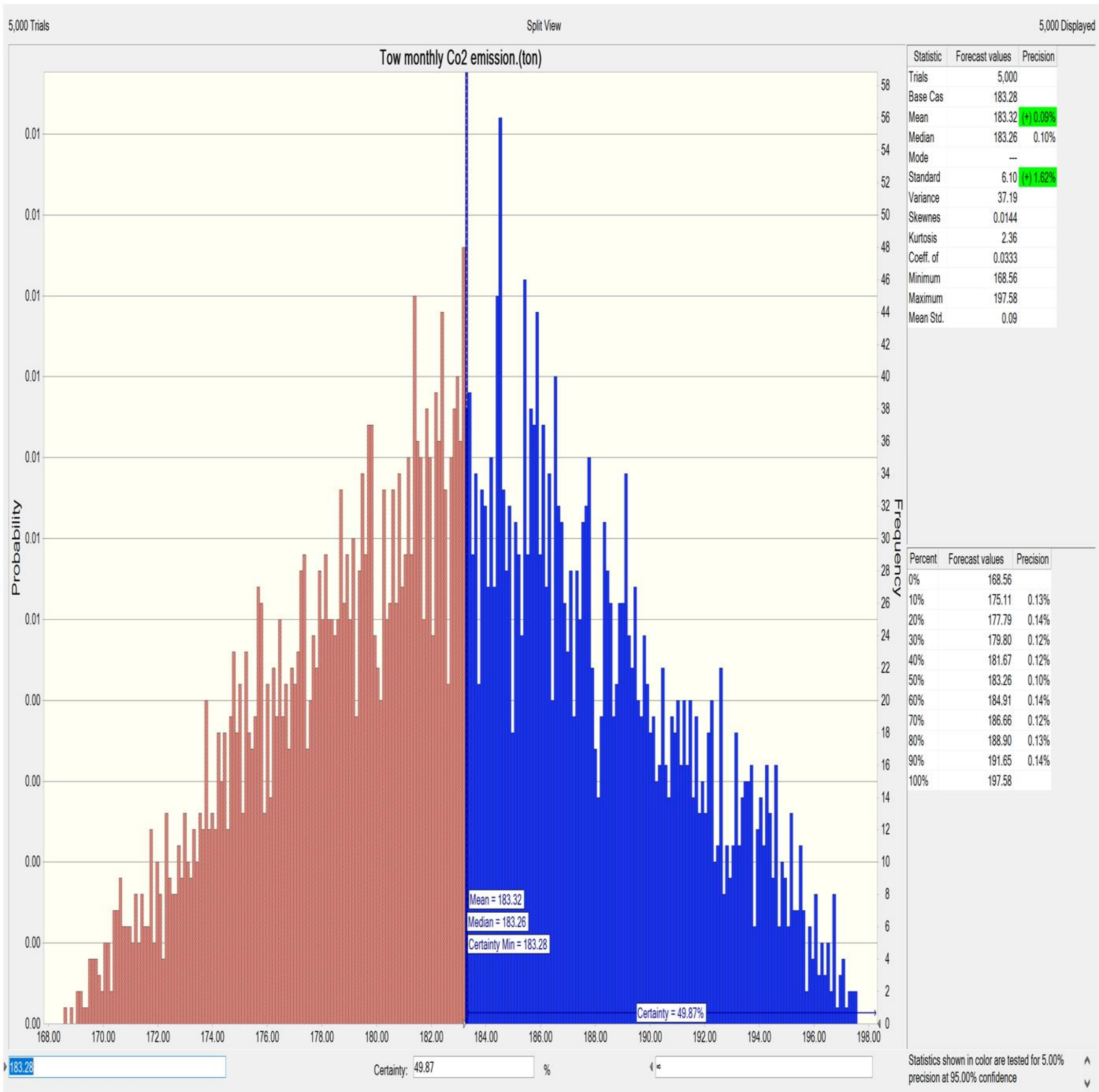


Fig 5.18. Monthly Co2 emission of the towing alternative.

TOPSIS Calculation and Sensitivity analysis

With respect to the importance of the issues, the attribute weights have been assumed to be as 0.3 for UWN pollution and monthly fuel cost, and 0.4 for monthly Co2 emission (all attributes are the cost). Table 5.4 and Figure 5.19 show the TOPSIS calculations and alternatives ranking with reference to equations No 9 to 15.

Table 5.4. TOPSIS calculations results in scenario 1.

	cost 1	SQRT	Normalised				Weight*Normalised=V				Pos Ideal=PI	Neg Ideal=NI
	benefit 0		X1=13.68	X2=10.5	X3=7	X4=Tow	X1=13.68	X2=10.5	X3=7	X4=Tow		
UWN pollution	1	366.3406	0.5109998	0.48706	0.450428	0.546595	0.1533	0.146118	0.135128334	0.163979	0.1351283	0.16397853
M.Co2 emission	1	567.8523	0.557328	0.532286	0.549439	0.32276	0.222931	0.212915	0.219775452	0.129104	0.129104	0.2229312
M.fuel cost	1	105900.2	0.5573248	0.532296	0.549438	0.322751	0.167197	0.159689	0.164831436	0.096825	0.0968253	0.16719744

	(V-PI)^2					(V-NI)^2			
	x1=13.68	x2=10.5	x3=7	x4=Tow		x1=13.68	x2=10.5	x3=7	x4=Tow
UWN pollution	0.00033	0.0001208	0	0.000832		0.000114	0.000319	0.000832334	0
M.Co2 emission	0.008804	0.0070242	0.008221	0		0	0.0001	9.95876E-06	0.008804
M.fuel cost	0.004952	0.0039518	0.004625	0		0	5.64E-05	5.59796E-06	0.004952
SPI	0.118684	0.1053413	0.113341	0.02885	SPN	0.010679	0.021811	0.029118562	0.117285

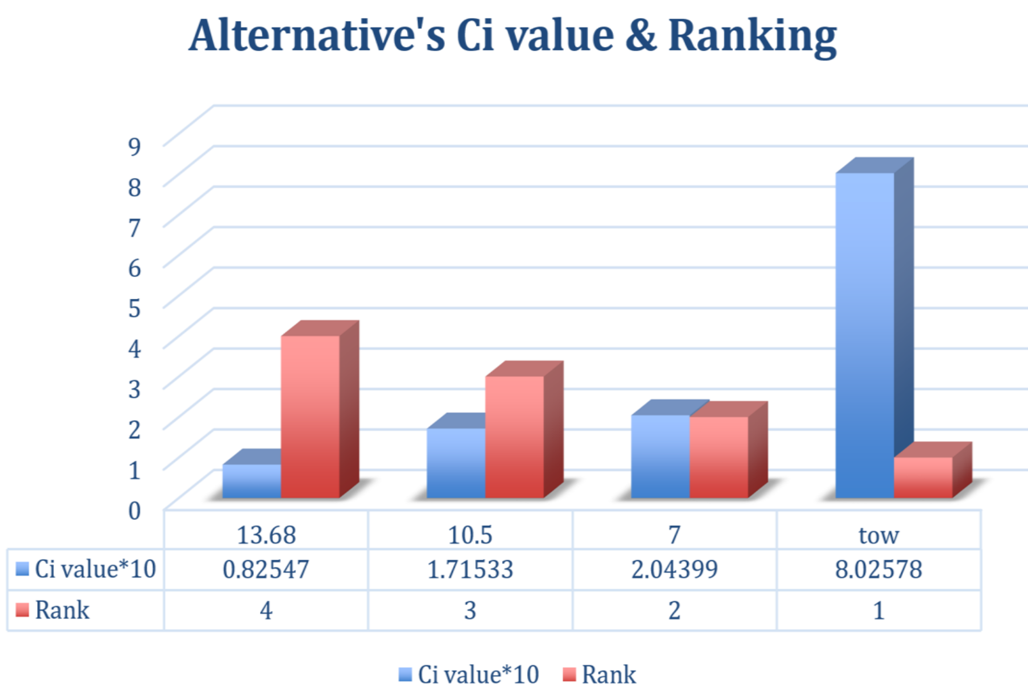


Fig 5.19. The alternatives C_i and ranking of scenario 1.

As Figure 5.19 shows, although the towing alternative is much noisier than the second best option (7 knots alternative), due to its significant privilege in less fuel consumption, fuel cost, and Co2 emission (% 41.25), it placed in the first place of ranking. The 7 knots alternative, due to being a quieter vessel in comparison with the other alternatives (13.42 dB less than the 10.5 knots with MSL of 178.43 dB), placed in the second position in the ranking. The 10.5 knots and 13.68 knots alternatives are placed in third and fourth place in the ranking, respectively.

Table 5.5 below demonstrates the result of the sensitivity analysis, which will make the environment clearer in order to enhance the DSS.

Table 5.5. The sensitivity analysis in scenario 1.

Sensitivity analysis									
	Model values	13.68	Change	10.5	Change	7	Change	Tow	change
At.w noise	0.3	0.2	-33.33	0.7	133.33	0.7	133.33	0.2	-33.33
At.W T.F.Cost	0.3	0.1	-66.67	0.1	-66.67	0.1	-66.67	0.6	100
At.w emission	0.4	0.7	75	0.2	-50	0.2	-50	0.2	-50
Emission Tow	183.280	200.244	9.2558	201.628	10.011	201.628	10.011	186.796	1.9184
Emission 10.5	302.260	274.573	-9.16	272.03	-10	332.48	9.998	332.48	9.998
Emission 13.68	316.480	284.830	-10	348.12	9.9975	348.12	9.9975	284.83	-10
Emission 7	312.000	343.200	10	343.2	10	280.8	-10	280.8	-10
Noise Tow	200.240	198.249	-0.994	202.249	1.0033	202.249	1.0033	198.249	-0.994
Noise 13.68	187.200	189.200	1.0684	189.2	1.0684	186.027	-0.627	185.2	-1.068
Noise 7	165.010	163.010	-1.212	167.01	1.212	163.01	-1.212	167.01	1.212
Noise 10.5	178.430	176.430	-1.121	176.43	-1.121	176.43	-1.121	176.43	-1.121
T.F.CostcTow	34179.400	30761.460	-10	30761.46	-10	30761.46	-10	30761.46	-10
T.F.Costc 13.68	59020.800	62867.443	6.5174	64922.88	10	64022.943	8.4752	58430.6	-1
T.F.Cost 7	58185.600	52367.040	-10	52367.04	-10	62719.213	7.7916	64004.16	10
T.F.Cost 10.5	56370.200	62007.220	10	50733.18	-10	59678.123	5.8682	50733.18	-10
Maximize Ci value		ci=0.4		Ci=0.62		Ci=0.67		Ci=0.92	
Rank(13.68,10.5,7,tow)	4,3,2,1	3,2,4,1		4,1,2,3		4,2,1,3		3,2,4,1	

Using data achieved in TOPSIS techniques, a sensitivity analysis was conducted for each alternative and maximization of their C_i value was done to find the optimum criteria for the alternatives. As the table reveals, the attribute weights have a significant effect on the maximization of the C_i values of the alternative. The attribute weight effects are so important that they can change the ranking of the alternatives. With dominant noise attribution weight (0.7), the 7 knots and the 10.5 knots alternatives have the capability to become the ideal options. However, the number of changes in other factors, such as total fuel cost and Co2 emission, determine which one is the best option.

By dominated Co2 emissions (0.7) and total fuel cost (0.6), the 7 knots alternative placed in 4th position and the towing alternatives, 10.5, and 7 knots are placed in first to third position of ranking, respectively.

5.2.1.2 The Inbound tankers
(Tugs noise change with speed Alteration)

This scenario is the same as scenario 1, with the only difference being that the amount of MSL from the towing alternative has been changed with speed alteration.

While the tankers UWN radiation has been calculated from equation No3 with benchmark the MSL of 187.2 dB for 13.68-knot speed. The UWN radiation for the accompanying tug at4 knots speed has been considered to change 3.4 dB per knot, with the benchmark the MSL of 189 dB for 12 knots (Jasco, 2014) and the towing tugs noise is considered 199.7 dB constant. Figure 5.20 demonstrates the MSL of the tankers and the tugs respectively.

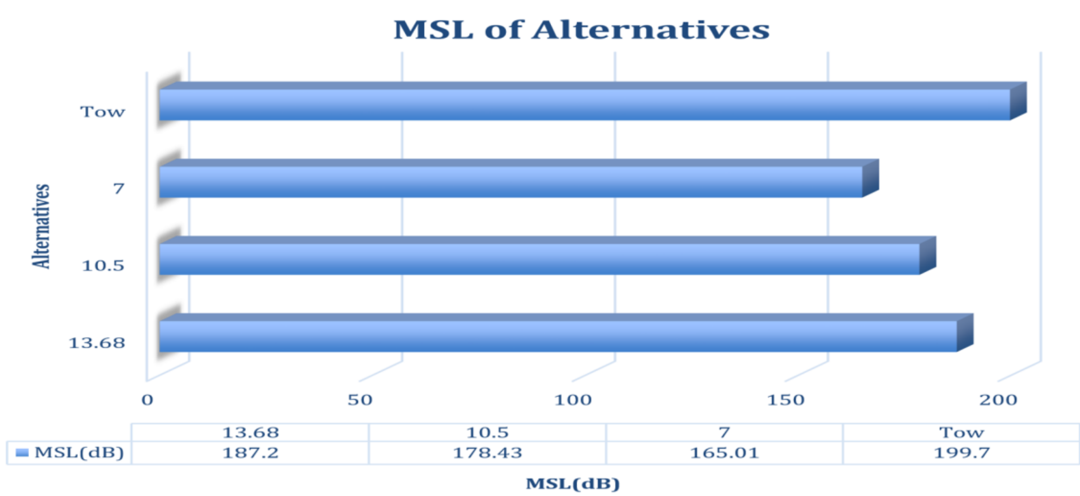
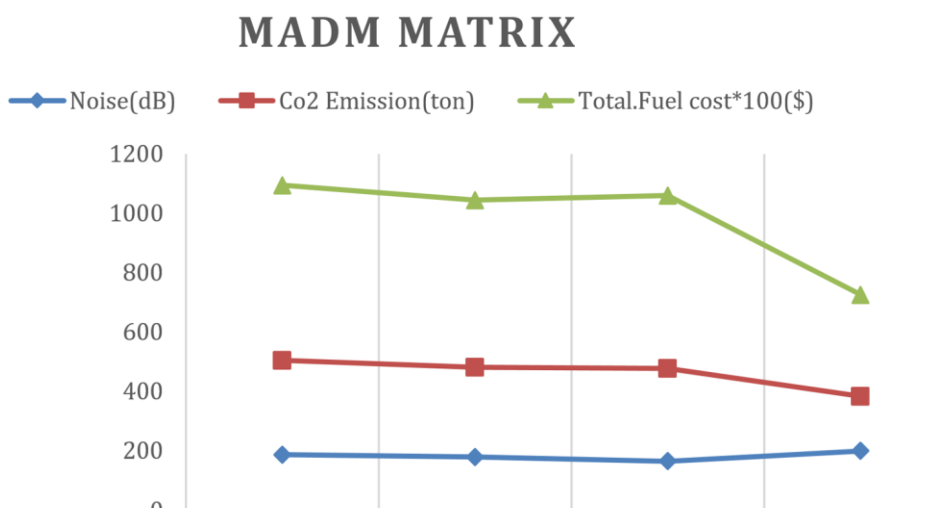


Fig 5.20. The MSL of different alternatives in scenario 2.

The Figure 5.21 illustrates the matrix of the MADM for TOPSIS calculations.



	13.68	10.5	7	Tow
Total.Fuel cost*100($)	590.208	563.702	581.856	341.794
Co2 Emission(ton)	316.489	302.26	312	183.28
Noise(dB)	187.2	178.43	165.01	199.7

Fig 5. 21. The MADM matrix of scenario 2.

TOPSIS Calculation and Sensitivity analysis

With respect to the attribution weight of 0.3 considered for UWN pollution and monthly fuel cost and 0.4 for Co2 emission (all attributes are the cost), the TOPSIS calculation and alternatives ranking were conducted by referring to equations No9 to 15. The results are shown in Table 5.6 and Figure 5.22.

Table 5.6. TOPSIS calculations results in scenario 2.

	cost 1	SQRT	Normalised				Weight*Normalised=V				Pos Ideal=PI	Neg Ideal=NI
	benefit 0		X1=13.68	X2=10.5	X3=7	X4=Tow	X1=13.68	X2=10.5	X3=7	X4=Tow		
UWN pollution	1	366.0458	0.511411	0.487453	0.450791	0.54556	0.153423	0.146236	0.135237	0.163668	0.13523719	0.16366806
M.Co2 emission	1	567.8523	0.557328	0.532286	0.549439	0.32276	0.222931	0.212915	0.219775	0.129104	0.12910399	0.2229312
M.fuel cost	1	105900.2	0.557325	0.532296	0.549438	0.322751	0.167197	0.159689	0.164831	0.096825	0.09682532	0.16719744

	(V-PI)^2					(V-NI)^2			
	x1=13.68	x2=10.5	x3=7	x4=Tow		x1=13.68	x2=10.5	x3=7	x4=Tow
UWN pollution	0.000331	0.000121	0	0.000808		0.000105	0.000304	0.000808	0
M.Co2 emission	0.008804	0.007024	0.008221	0		0	0.0001	9.96E-06	0.008804
M.fuel cost	0.004952	0.003952	0.004625	0		0	5.64E-05	5.6E-06	0.004952
SPI	0.118687	0.105342	0.113341	0.028431	SPN	0.010245	0.021462	0.028703	0.117285

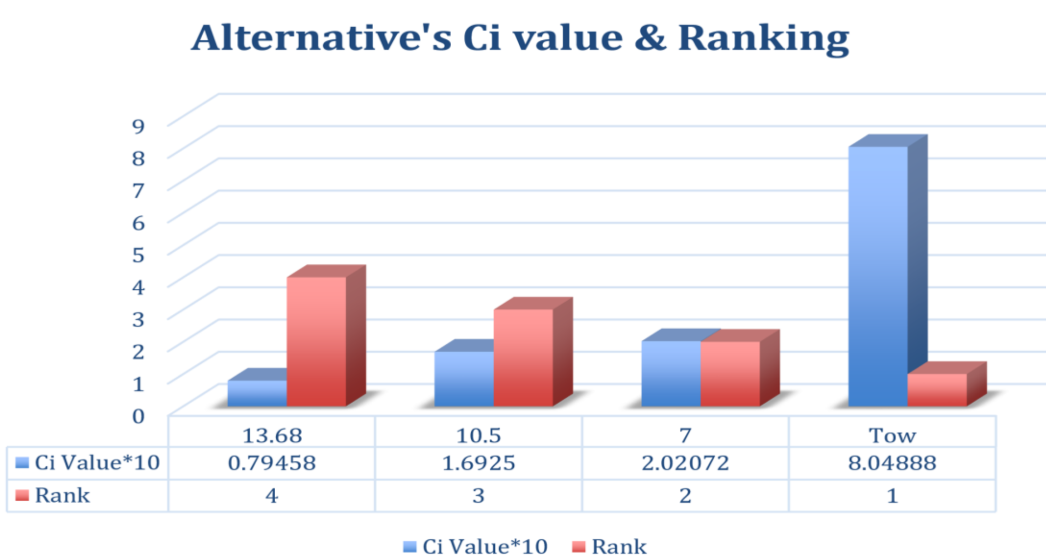


Fig 5.22. The alternatives C_i and ranking in scenario 2.

As Figure 5.22 demonstrates, there is not too much difference in C_i values of the alternatives and the ranking is the same as the first scenario. The towing alternative, due to its significant privilege in less fuel consumption, Co2 emission and fuel cost in comparison with other alternatives, placed in the first position in the ranking. Moreover, due to 0.54 dB reduction in its UWN radiation, its C_i value has increased slightly. The 7 knots alternative, due to being a quieter vessel in comparison with the other alternatives (13.42 dB less than the 10.5 knots with 178.43 dB), placed 2nd in ranking and the 10.5 knots and 13.68 knots alternatives placed in third and fourth position, respectively.

Table 5.7 below demonstrates the result of the sensitivity analysis for this scenario. As the table reveals, the attributions weights are the most effective factors in changing the alternative C_i value and their ranking. By considering the dominant weight for UWN radiation (0.8), the best alternative becomes the 7 knots speed due to its UWN radiation (165.01dB), which is significantly less than the next quieter alternative of 10.5-knot speed with 178.43 dB. This 13.42 dB difference is so effective that even in the maximization of the C_i value for the 13.68 and 10.5 knots, the 7 knots alternative placed in the first rank, such as its own C_i value maximized. The 10.5 knots, 13.68 knots speed and towing alternatives are placed, consequently, in the next ranking position.

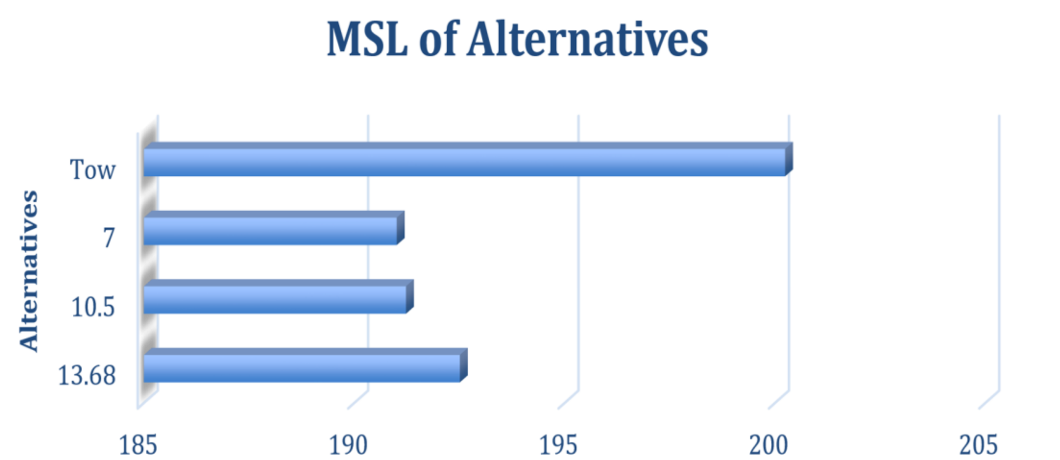
Table 5.7. The sensitivity analysis in scenario 2.

Sensitivity analysis									
	Model Value	13.68	Change	10.5	Change	7	Change	Tow	change
At.w noise	0.3	0.8	166.7	0.8	0	0.8	166.7	0.1	-66.67
At.W T.F.Cost	0.3	0.1	-66.67	0.1	-66.6667	0.1	-66.67	0.8	166.67
At.w emission	0.4	0.1	-75	0.1	-75	0.1	-75	0.1	-75
Emission Tow	183.280	201.680	10.04	201.68	10.03928	201.68	10.04	164.95	-10
Emission 10.5	302.260	272.030	-10	272.03	-10.0013	332.48	9.998	272.03	-10
Emission 13.68	316.480	284.830	-10	284.83	-10.0006	284.83	-10	348.12	9.9975
Emission 7	312.000	343.200	10	343.2	10	280.8	-10	343.2	10
Noise Tow	199.700	201.700	1.002	200.033	0.16675	201.7	1.002	197.7	-1.002
Noise 13.68	187.200	185.200	-1.068	185.2	-1.06838	185.2	-1.068	189.2	1.0684
Noise 7	165.010	167.010	1.212	167.01	1.212048	163.01	-1.212	167.01	1.212
Noise 10.5	178.430	180.430	1.121	176.43	-1.12089	176.43	-1.121	176.43	-1.121
T.F.CostcTow	34179.400	30761.460	-10	37597.4	10.00018	37597.4	10	30761.5	-10
T.F.Costc 13.68	59020.800	64922.880	10	58430.6	-0.99999	64922.88	10	64922.9	10
T.F.Cost 7	58185.600	64004.160	10	52367.04	-10	52367.04	-10	52367	-10
T.F.Cost 10.5	56370.200	62007.220	10	50733.18	-10	62007.22	10	50733.2	-10
Maximize Ci value		Ci=0.42		Ci=0.66		Ci=0.82		Ci=0.97	
Rank(13.68,10.5,7,tow)	4,3,2,1	3,2,1,4		3,2,1,4		3,2,1,4		4,2,3,1	

However, with the dominant total fuel cost weight (0.8), due to higher fuel consumption price and Co2 emission, the 7 knots speed placed in third position after the towing and 10.5-speed alternatives, which are placed in the first and second position of ranking, respectively.

5.2.1.3 The outbound tankers
(Tugs noise constant with speed alteration)

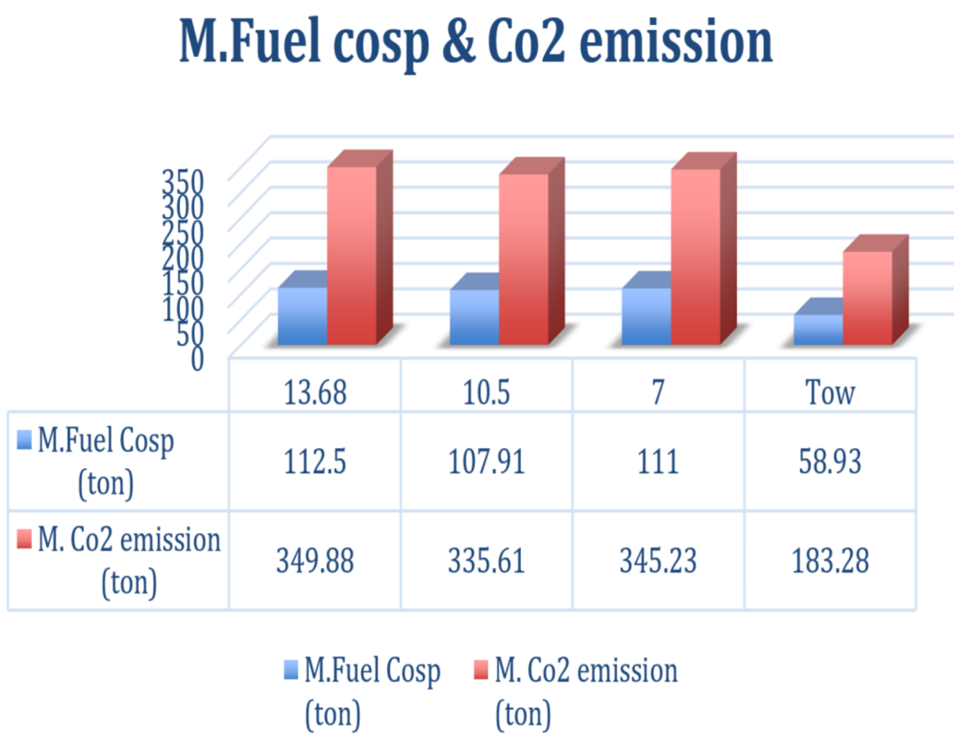
As explained before, to enhance safety and reduce the likelihood of navigational incidents and any oil spill, the outbound tankers should be escorted with one tug from the Westridge Terminal to Buoy J where the Juan De Fuca Strait ends at the Pacific Ocean (NEB a, 2016). In this scenario the outbound tankers are considered with the accompaniment of one tug (tethered) during the passage of the Haro Strait (16 nm).The tug is considered to radiate constant UWN with MSL of 191 dB for all speeds and MSL of 199.7 dB for the towing tug, in the towing alternative. The UWN radiation for tankers is based on the average MSL value of 187.2 dB for 13.68 knots and with reference to equation No3 is calculated for alternative speeds of 10.5 and 7 knots. The MSL of the tankers and the tug, same as the sum of the escorting tug and the towing tug MSLs (in towing alternatives), have been calculated by reference to equation No4. The results of UWN radiation from all alternatives are demonstrated in Figure 5.23.



	13.68	10.5	7	Tow
MSL(dB)	192.51	191.23	191.01	200.24

Fig 5.23. The MSL of different alternatives for scenario 3.

The total fuel consumption of the tanker and the tug while transiting the study area are calculated by referring to equation No5. Then by referring to equation No6, the total monthly fuel consumption of the tanker and the tug are achieved, accordingly.
By equations No7 and 8, total monthly CO_2 emission and total fuel cost have been calculated, respectively. Figures 5.24 and 5.25 illustrates the monthly fuel consumption, CO_2 emission, and total monthly fuel cost, respectively.



	13.68	10.5	7	Tow
M.Fuel Cosp (ton)	112.5	107.91	111	58.93
M. Co2 emission (ton)	349.88	335.61	345.23	183.28

Fig 5.24. Monthly fuel consumption and Co2 emission of scenario 3.

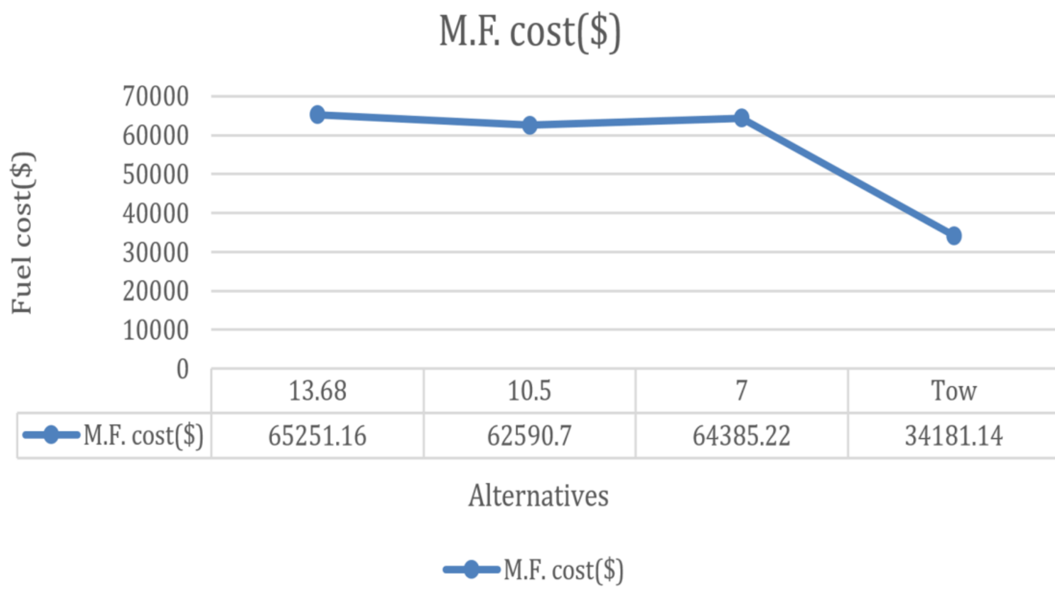


Fig 5.25. Total monthly fuel cost of scenario 3.

With respect to the calculated data, the MADM matrix has been created as Figure 5.26 illustrates;

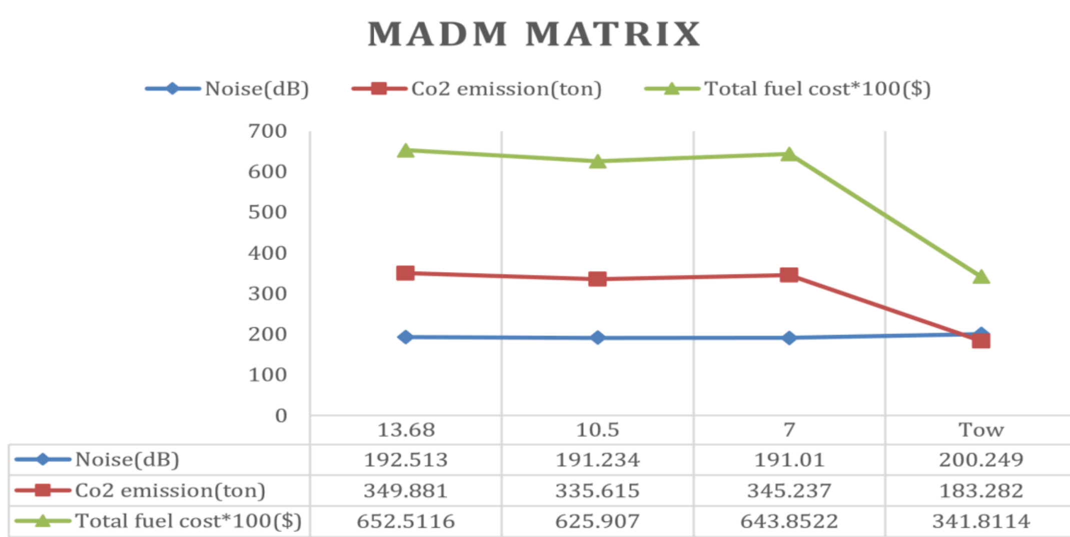


Fig 5.26. The MADM matrix of scenario 3.

TOPSIS Calculation and Sensitivity analysis

With respect to the alternatives weights, which are 0.3, 0.4, and 0.3 for the UWN pollution, Co2 emission, and monthly fuel cost, respectively (all attributes are the cost), the TOPSIS calculation and alternative ranking is conducted by referring to equations No9 to 15.

The results are shown in Table 5.8 and Figure 5.27.

Table 5.8. TOPSIS calculations results in scenario 3.

	cost 1	SQRT	Normalised				Weight*Normalised=V				Pos Ideal=PI	Neg Ideal=NI
	benefit 0		X1=13.68	X2=10.5	X3=7	X4=Tow	X1=13.68	X2=10.5	X3=7	X4=Tow		
UWN Pollution	1	387.5773	0.496709	0.493409	0.492831	0.51666852	0.149013	0.148023	0.147849	0.155001	0.1478492	0.15500056
M. Co2 emission	1	622.764	0.56182	0.538912	0.554362	0.29430409	0.224728	0.215565	0.221745	0.117722	0.1177216	0.22472782
M.fuel cost	1	116142.7	0.561819	0.538912	0.554363	0.29430307	0.168546	0.161674	0.166309	0.088291	0.0882909	0.16854572

	(V-PI)^2					(V-NI)^2			
	x1=13.68	x2=10.5	x3=7	x4=Tow		x1=13.68	x2=10.5	x3=7	x4=Tow
UWN Pollution	1.35E-06	3.01E-08	0	5.11E-05		3.59E-05	4.87E-05	5.11E-05	0
M. Co2 emission	0.01145	0.009573	0.010821	0		0	8.4E-05	8.9E-06	0.01145
M.fuel cost	0.006441	0.005385	0.006087	0		0	4.72E-05	5E-06	0.006441
SPI	0.133763	0.122304	0.13003	0.007151	SPN	0.005988	0.013412	0.008065	0.133758

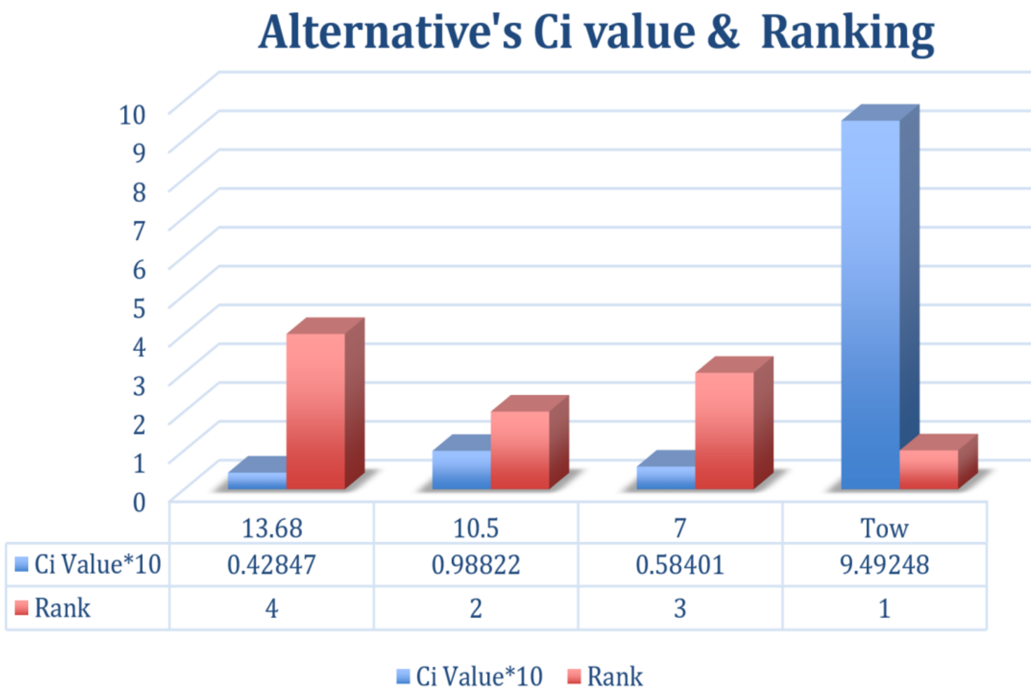


Fig 5.27. The alternatives C_i and ranking of scenario 3.

As Figure 5.27 shows, the towing alternative is placed in the first rank. Although the towing UWN radiation is 9 dB more than the 10.5 knots, due to its 45.38% privilege in less fuel consumption, fuel cost, and Co2 emission in comparison with the second best alternative (10.5 knots), it placed in the first rank. The 7 and 13.68 knots speed alternatives placed in the third and fourth ranking positions, respectively. It is because of the 2.78% and 4.08% privilege of 10.5 knots alternative in less fuel consumption, fuel cost, and Co2 emission in comparison to 7 and 13.68 knots.

Table 5.9 below demonstrates the sensitivity analysis of this scenario. As the table reveals, the attributions weights are the most effective factors in changing the alternatives C_i value and their ranking. The towing has enjoyed from it's beneficial in less fuel consumption, cost, and Co2 emission (45.38%) and placed in the first rank in all C_i value maximization. Meanwhile, the 10.5 knots alternative by dominating the Co2 emission attribute’s weight (0.7) placed in the second position after the towing alternative.

Table 5.9. The sensitivity analysis in scenario 3.

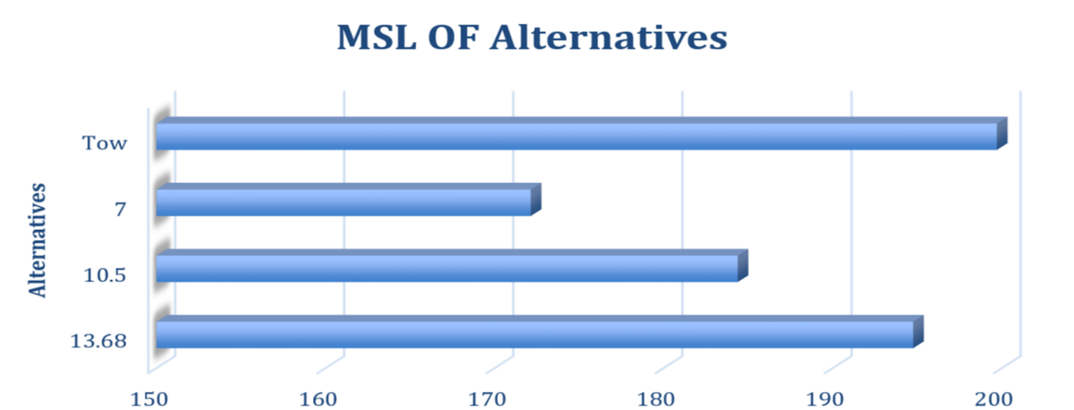
Sensitivity analysis									
	Model values	**13.68**	**Change**	**10.5**	**Change**	**7**	**Change**	**Tow**	**change**
At.w noise	0.3	0.7	133.33	0.2	-33.3	0.7	133.3	0.2	-33.33
At.W T.F.Cost	0.3	0.1	-66.67	0.1	-66.7	0.1	-66.67	0.1	-66.67
At.w emission	0.4	0.2	-50	0.7	75	0.2	-50	0.7	75
Emission Tow	183.282	201.609	9.9993	201.609	9.999	201.609	9.999	164.952	-10
Emission 10.5	335.615	302.050	-10	302.05	-10	302.05	-10	302.05	-10
Emission 13.68	349.881	315.000	-9.969	385	10.04	385	10.04	385	10.04
Emission 7	345.237	379.750	9.9969	379.75	9.997	310.7	-10	379.75	9.997
Noise Tow	200.249	202.249	0.9988	202.249	0.999	198.249	-0.999	198.249	-0.999
Noise 13.68	192.513	190.510	-1.04	194.51	1.037	194.51	1.037	194.51	1.037
Noise 7	191.010	189.010	-1.047	193.01	1.047	189.01	-1.047	193.01	1.047
Noise 10.5	191.234	189.234	-1.046	193.234	1.046	189.234	-1.046	193.234	1.046
T.F.CostcTow	34181.140	30763.026	-10	37599.24	10	30763	-10	30763	-10
T.F.Costc 13.68	65251.160	58726.044	-10	71776.28	10	71776.3	10	71776.6	10
T.F.Cost 7	64385.220	70823.740	10	70823.74	10	57946.7	-10	70823.7	10
T.F.Cost 10.5	62590.700	56331.360	-10	56331.36	-10	68849.4	9.999	56331.4	-10
Maximize Ci value		ci=0.42		Ci=0.45		Ci=0.43		Ci=0.99	
Rank(13.68,10.5,7,tow)	4,2,3,1	3,2,4,1		4,2,3,1		4,3,2,1		4,2,3,1	

However, by the domination of the noise attribute weight (0.7), the other factors such as total fuel cost and Co2 emission play the role to position the 10.5 or 7 knots alternatives as the best second option. During the maximization of the 13.68-knot alternatives, the 10.5 knots alternative becomes the second option and 7 knots placed in the fourth rank after the 13.68-knot alternative. The 7 knots alternative only during its own maximization placed in the second position after the towing alternative, and the 10.5 and 13.68-knot speed alternatives placed in third and fourth-ranking position.

5.2.1.4 The outbound tankers
(Tugs noise change with speed variation)

In this scenario as in the previous one, the tankers are escorted by one tug in the studied area, but in contrast to the previous one, the tugs noise is considered to change with variable speeds. All figures for the MADM matrix are the same as for scenario 3, with the only difference being that the amount of MSL from the all alternatives have changed.

The tankers UWN radiation has been calculated by equation No3, with average MSL of 187.2 dB for 13.68-knot speed. The UWN radiation for the accompanying tug at all alternatives speed has been considered to change 3.4 dB per knot, with the benchmark of the 189 dB for 12 knots (Jasco, 2014), and the towing tugs noise is considered to be 199.7 dB constant. With respect to equation No4, the MSL of the tanker summed up with MSL of the accompany tug in each alternative and the following has been achieved, as per Figure 5.28.

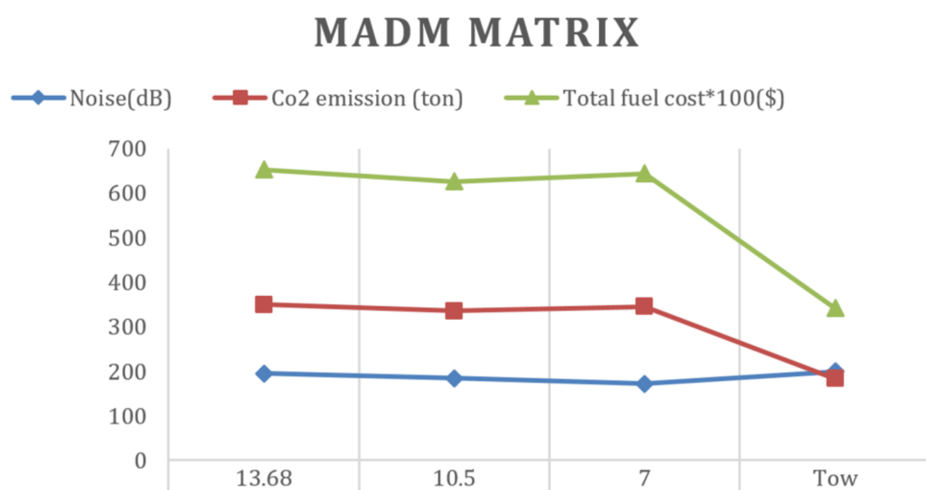


	13.68	10.5	7	Tow
MSL(dB)	194.75	184.37	172.13	199.7

MSL(dB)

Fig 5.28. The MSL of different alternatives of scenario 4.

Figure 5.29 demonstrates the data of the MADM matrix.



	13.68	10.5	7	Tow
Noise(dB)	194.75	184.37	172.13	199.7
Co2 emission (ton)	349.881	335.615	345.23	183.281
Total fuel cost*100($)	652.5116	625.907	643.8522	341.8114

Fig 5.29. The MADM matrix of scenario 4.

TOPSIS Calculation and Sensitivity analysis

With respect to the attribution weight, which is 0.3 for the UWN pollution, and monthly fuel cost and 0.4 for monthly Co2 emission (all attributes are the cost), the TOPSIS calculation and alternatives ranking was conducted by referring to equations No9 to 15. The results are shown in Table 5.10 and Figure 5.30.

Table 5.10. The TOPSIS calculations results in scenario 4.

	cost 1 / benefit 0	SQRT	Normalised				Weight*Normalised=V				Pos Ideal=PI	Neg Ideal=NI
			X1=13.68	X2=10.5	X3=7	X4=Tow	X1=13.68	X2=10.5	X3=7	X4=Tow		
UWN pollution	1	376.1873	0.517907	0.490314	0.457777	0.530853	0.155372	0.147094	0.137333	0.159256	0.137333175	0.15925576
M.Co2 emission	1	622.7598	0.561823	0.538916	0.554355	0.294304	0.224729	0.215566	0.221742	0.117722	0.117721785	0.22472933
M.fuel cost	1	116142.5	0.56182	0.53891	0.554364	0.294303	0.168546	0.161673	0.166309	0.088291	0.088291043	0.16854596

	(V-PI)^2					(V-NI)^2			
	x1=14	x2=10.5	x3=7	x4=Tow		x1=14	x2=10.5	x3=7	x4=Tow
UWN pollution	0.000325	9.53E-05	0	0.000481		1.51E-05	0.000148	0.000481	0
M.Co2 emission	0.011451	0.009574	0.01082	0		0	8.4E-05	8.92E-06	0.011451
M.fuel cost	0.006441	0.005385	0.006087	0		0	4.72E-05	5E-06	0.006441
SPI	0.13497	0.122694	0.130027	0.021923	SPN	0.003884	0.016706	0.022238	0.133759

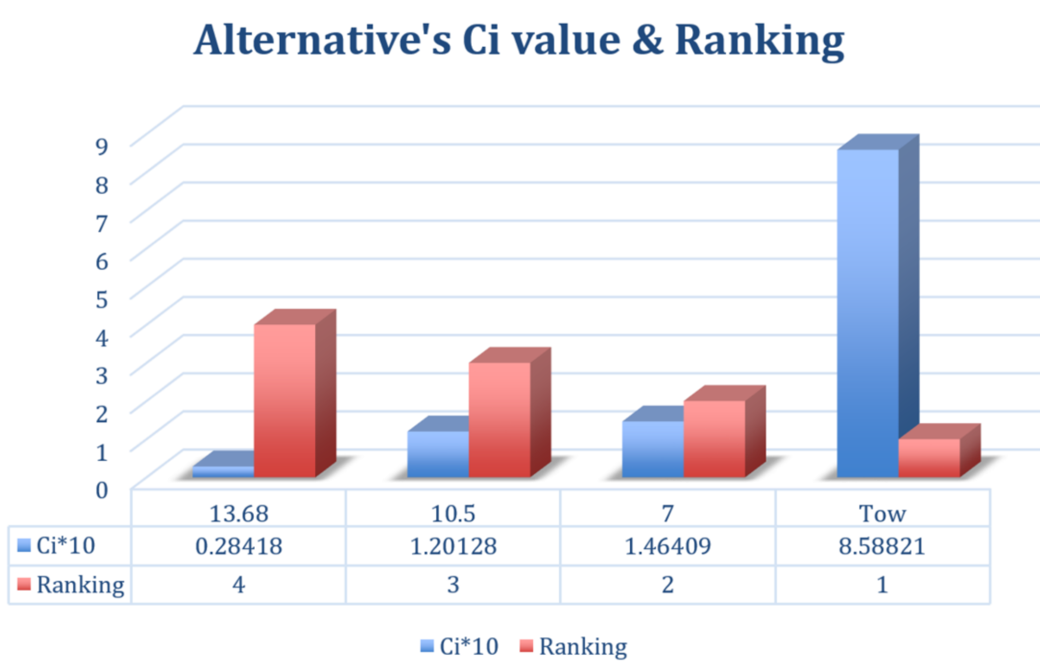


Fig 5.30. The alternatives C_i and ranking of the scenario 4.

As Figure 5.30 illustrates, the towing alternative with its significant privilege in less fuel consumption, fuel cost, and Co2 emission (46.9%), in comparison with the second best alternative (7 knots), placed in the first rank. In contrast to scenario 3, although the 7 knots alternative had 2.78% more fuel consumption, Co2 emission, and fuel cost in comparison to the 10.5-knot alternative, the 7 knot alternative placed in second position due to it lower UWN radiation (12.24 dB). The 13.68 knots alternative placed in the fourth place as in the previous scenarios.

As the Table 5.11 shows, in the sensitivity analysis, the attribute weights are the dominant factors in changing the ranking and the alternative's C_i values. Considering 0.8 for the attribute weight of the UWN, the 7 knots alternative becomes the first option in ranking. This is because of the dominant difference between UWN radiation from 7 knots and other alternatives.

Table 5.11. The sensitivity analysis in scenario 4.

Sensitivity analysis									
	Model Value	13.68	Change	10.5	Change	7	Change	Tow	Change
At.w noise	0.3	0.1	-66.67	0.8	0	0.8	166.66	0.1	-66.67
At.W T.F.Cost	0.3	0.1	-66.67	0.1	-66.7	0.1	-66.667	0.1	-66.67
At.w emission	0.4	0.8	100	0.1	-75	0.1	-75	0.8	100
Emission Tow	183.281	201.609	10	164.95	-10	201.61	9.9999	201.61	10
Emission 10.5	335.615	302.05	-10	302.05	-10	369.17	9.9981	302.05	-10
Emission 13.68	349.881	315	-9.969	315	-9.97	315	-9.9694	315	-9.969
Emission 7	345.23	379.75	9.999	310.7	-10	310.7	-10.002	379.75	9.999
Noise Tow	199.7	197.7	-1.002	201.7	1.002	201.7	1.0015	197.7	-1.002
Noise 13.68	194.751	192.83	-0.986	195.49	0.378	192.83	-0.9864	196.83	1.068
Noise 7	172.136	174.21	1.205	170.21	-1.12	170.21	-1.1189	174.21	1.205
Noise 10.5	184.377	182.45	-1.045	182.45	-1.05	182.45	-1.0451	186.32	1.054
T.F.CostcTow	34181.14	37599.24	10	37599	10	37599	10	37599	10
T.F.Costc 13.68	65251.16	71776.28	10	71776	10	71776	10	71776	10
T.F.Cost 7	64385.22	70823.74	10	57947	-10	57947	-10	70824	10
T.F.Cost 10.5	62590.4	58635.03	-6.319	56331	-10	68849	10	56331	-10
Maximize Ci value		Ci=0.36		Ci=0.52		Ci=0.74		Ci=0.97	
Rank (13.68,10.5,7,tow)	4,3,2,1	3,2,4,1		4,2,1,3		4,2,1,3		3,2,4,1	

However, after changing the attribute weight of emission to 0.8, it falls to fourth place in the ranking and the towing option goes back to the first ranking. The 10.5 knots alternative keeps the second best alternative in all maximization and 13.68 knots placed in third position in the dominant emission attribution weight, and earned the fourth position for the dominant UWN attribution weight.

5.2.1.5 Summary of the Scenarios

Table 5.12 illustrates the final results of all scenarios.

Table 5.12. Final results of all scenarios.

Alternative speeds	13.68		13.68		10.5		10.5		7		7		Tow		Tow	
Types of the Scenario	Inbound		out bound		Inbound		out bound		Inbound		out bound		Inbound		out bound	
Tugs SML condition (Constant) or (Change)	constant	change	constant	change	constant	change	constant	change	constant	change	constant	change	constant	change	constant	change
Noise(dB)	187.2	187.2	192.513	194.75	178.43	178.43	191.234	184.37	165.01	165.01	191.01	172.13	200.24	199.7	200.249	199.7
Emission(tn)	316.48	316.48	349.881	349.881	302.26	302.26	335.615	335.615	312	312	345.237	345.23	183.28	183.28	183.282	183.281
F.cost($)	59,020.80	59,020.80	65,251.16	65,251.16	56,370.20	56,370.20	62,590.70	62,590.70	58,185.60	58,185.60	64,385.22	64,385.22	34,179.40	34,179.40	34,181.14	34,181.14
Alternative's ranking in each Scenarios	4	4	4	4	3	3	2	3	2	2	3	2	1	1	1	1
Maximised Ci value & related ranking after maximization (13.68,10.5,7,Tow)	Ci=0.4 3,2,4,1	Ci=0.42 3,2,4,1	Ci=0.42 3,2,4,1	Ci=0.36 3,2,4,1	Ci=0.62 4,1,2,3	Ci=0.66 3,2,1,4	Ci=0.45 4,2,3,1	Ci=0.52 4,2,1,3	Ci=0.67 4,2,1,3	Ci=0.82 3,2,1,4	Ci=0.43 4,3,2,1	Ci=0.74 4,2,1,3	Ci=0.92 3,2,4,1	Ci=0.97 4,2,3,1	Ci=0.99 4,2,3,1	Ci=0.92 3,2,4,1

As it shows, the towing alternative is the first option between all alternatives in all scenarios due to its privilege in less fuel consumption, less fuel cost and CO_2 emission in comparison with other alternatives. The 7 knots alternative not only in both inbound scenarios, but also in the outbound ones (variable UWN for the tug), placed in the second rank due to its excellent condition in UWN radiation in comparison with the other options. However, in the outbound scenarios (Constant UWN for tug), it is placed in third position due to becoming noisier (191 dB), with more fuel consumption, CO_2 emission and fuel cost. The 10.5 knots alternative in all scenarios (except outbound with constant UWN for tug) placed in third position after the towing and 7 knots alternatives, respectively, and the 13.68 knots alternative placed in fourth place in all scenarios.

The safety and economic aspects in respect of delay due to slow steaming are not in the scope of this study. While the towing option may be claimed due to its large delay and endangering the safety of the navigation (it needs for further study), the time difference between 7 and 10.5 knots in transiting the study area (16 nm) is around 46 minutes, which requires further study regarding the side effects of this delay in respect of the different stakeholders.

Moreover, the study shows that the tugs play a significant role in developing the sustainable shipping in the area and the role becomes more significant after the commencement of the Westridge Terminal operation. It requires more efficient, and quieter tugs to be used in the area. Using tugs with LNG and methanol engines, or using fuel cells and hybrid batteries on the tugs can have significant roles in reducing both emissions and the UWN radiation. In parallel with study and investment for mitigation of UWN radiation from the commercial vessels, it is necessary to pay more attention to tugs.

The sensitivity analysis of the scenarios demonstrates the effect of mindset and selecting the attribute weights which can totally change the best alternative option. It is necessary to conduct a comprehensive study to evaluate and choose the best attribution weights in the general trend of the port authority. It is also crucial to consider the multi-dimensional thinking instead of the single dimensional thinking in addressing and tackling the issues.

5.2.2 Air Bubble curtain

In order to reduce the UWN footprint, several mitigation techniques have been investigated in the literature. Among the various solutions proposed, the air-bubble curtain is often applied due to the simplicity of its application and the impression of noise reduction (Domenico, 1982). The Air Bubble Curtain (ABC) was firstly proposed by Adolph in the 1940s and was applied in underwater blasting at the Ontario hydropower station in Canada (Tu, 2014). Now it is not only used in reducing UWN but also in many other industrial aspects, such as protecting port facilities like emergency evacuation bases from oil spill incidents acts as a countermeasure for blocking or eliminating floating oil from the facilities (Fujita, 2016).

The ABC technology mitigates negative effects of sound propagation on the marine environment by spatial or /and temporal closure of areas, to protect species from the source of noise or reduce the sound radiation (Tougaard et al., 2003). Two primary mechanisms play a role in the mitigation of sound in this method. First, sound travels 4.5 times faster in water than in the air. The creation of an air bubble curtain produces a boundary layer in the area and reduces the noise travelling speed and makes a proper scatters. Second, the bubbles absorb sound energy directly. When UWN arrives at the bubble curtain, the noise wave diffuses on the bubbles surface and the noise energy is absorbed by the bubbles and they become compressed. As a result, the noise propagation is mitigated (Tu, 2014).

ABC technology is common in both offshore fields and ports (Dragon, 2016). The noise propagation from pile driving during installation of jackets, wind turbines, expanding port jetties, and harbour walls can decay with the ABC technology (Göttsche et al., 2013). The amount of noise reduction depends on the frequency content of the radiated sound and the characteristics of the bubbly medium (Hu et al., 2014; Tsouvalas and Metrikine, 2016). As per Lucke, et.al, (2011) the ABC technology has been used successfully in different projects (California Department of Transportation, 2001; Reyff, 2003a, 2003b; Vagle, 2003; Matuschek and Betke, 2009). However, each has achieved a different level of success in UWN mitigation and has encountered different logistic problems and cost efficiency. For example, in Kerteminde harbor (Denmark), reduction in sound level by 14 dB on average was achieved (Lucke et al., 2011) and in Chek Lap Kok airport south of Sha Chau in Hong Kong, at distances of 250, 500, and 1000 m and the sound intensities of 100 HZ to 25.6 kHz, pulse levels were reduced by only 3 to 5 dB (Würsig et al., 2000).

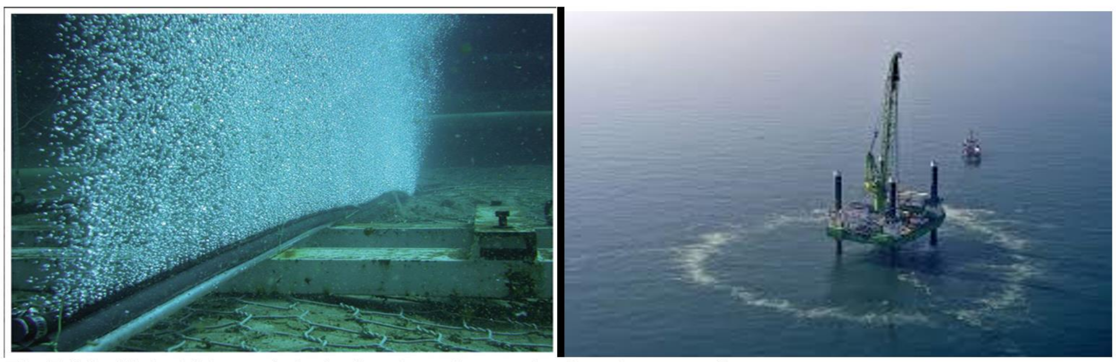


Fig 5.31. Air bubble curtain technology in sea bed and sea surface.
Source: (https://canadianpond.ca)

Haro Straight is a contingency area with high traffic density. The majority of ocean-going vessels transiting to Vancouver and vice versa pass through this corridor. Meanwhile, a high density of the SRKWs (especially in summer) is present in the area. The UWN effects the mammals' behaviour, masking their communication, decreasing their foraging efficiency, damaging their hearing, and affecting their population recovery (NOAA, 2018). In this respect, action should be taken to reduce UWN to achieve sustainable shipping in the area.

In Chapter 3, different mitigation measures were introduced to decay UWN propagation. However, none of them suggested and introduced any technologies and measurements to reduce noise between the ships and the noise receiver. By creating a buffer and noise absorber between the source of noise (commercial vessels) and the receivers (marine habitat) the amount and power of the received noise can be decreased. The ABC technology with respect to its efficient results in reducing noise in different in offshore /port fields projects (Dragon, 2016) has the capability to be considered as such a technology. However, it needs further study and optimization.

The ABC strongly mitigates sounds in frequencies that whales are known to communicate in (Ridgway,1983). Haro Strait, due to the geographical condition of the area, which is a narrow passageway, and also the presence of the SRKWs, can be a good place to conduct a study and evaluate the efficiency of ABC technology. As ABC gets nearer to the source of noise, its efficiency increases (Tu, 2014). Furthermore, the efficiency of such an air bubble system in open water should be optimized with respect to the strong current and increased depth. The acoustical tests show that a dense bubble curtain consisting of many small bubbles has the best sound mitigation effect (Rustemeier, 2012). By increasing the total amount of air per unit of time, the mitigation efficiency can be improved. Meanwhile, by decreasing the pressure in upper layers, the air bubbles expand and the system encounters a series of slowly rising micro-bubbles to large bubbles of a few centimetres in diameter (Würsig et al., 2000), which decrease the efficiency of the ABC. In order to compensate for this problem, two different systems of ABC can be used at different depths to cover all depths with high density and proper bubble curtains.

Any mitigation effects achieved from the system will help to reduce the impact of underwater on the marine environment. It is suggested to assess the effects of this technology in reducing noise propagation by the adoption of the features with the area condition and specification. By creating such an air bubble curtain in the Haro Strait, which is an important area for SRKW, the propagation of the noise and masking of whale communication can probably be reduced. Meanwhile, conducting such a study and utilizing the ABC technology in the area requires some assumptions and precautions, of which considering the safety of navigation is the most important.

5.2.3 Cold ironing

Global warming is one of the most important contemporary issues that has occurred due to the accumulation of GHG in the atmosphere through human activities (IPCC, 2013). Shipping is the backbone of trade and 90 percent of transport is carried out by shipping (Buhaug et al. 2009). In accordance with the IMO 2nd Greenhouse Gas Study, 2.7 percent of the global GHG emission is from international shipping.

Ports are the gateway to the land and the oceans. Many ports are located in the vicinity of residential areas (IMO-MSC, 2017), and are severely impacted by negative externalities from ship operations such as air pollution (a heavy social and environmental cost to the society) (Tarnapowicz and German-Galkin, 2018), which also contributes in global warming (Innes and Monios, 2018).

The fueled generator is a source of noise and vibration on vessels (Tarnapowicz and Borkowski, 2014), and as Wright, (2008) reveals it is one of the sources of machinery in the radiation of UWN. The highest noise intensity produced by vessels generators in port is within the range of 20–2,000 Hz, which attracts a variety of marine invertebrate larvae to settle on the ship's hull. By using the diesel generator during the ships' port stay, the formation of fouling such as mussels and ascidian larvae on the ship's hull is increased (Stanley et al., 2016). By the formation of the fouling on the ship's hull, the resistance, fuel consumption and emissions will increase. Furthermore, the wake inflow to the propeller will become inhomogeneous and the efficiency of the propulsion will decrease and, in contrast, the cavitation and UWN radiation will increase (Veritas & DNV, 2015). Moreover, the formation of fouling on the ship's hull will increase the spread of invasive species in the environment.

Optimization of ship handling and consideration of sustainability in port activities by balancing between economic, social, and environmental aspects can reduce the ships' negative externalities. In order to mitigate the negative externalities of shipping on society, many sustainable technologies have been developed in ports (Sanes et al., 2017).

Many ports are developing technologies such as cold ironing to reduce emissions from ships during their port stay. Cold Ironing provides the demanded electrical power to the berthed ship and lets the ship stop running its diesel-fueled generator during its stay in port (Sciberras et al.,2016). Although the system is not a zero emission, since it provides the required power to the ship in the port from the national grid, which is subjected to stricter emission control (Ballini and Bozzo, 2015), the amount of emission is much less than from the ships' fuel generator. Furthermore, cold ironing not only reduces emissions, but also reduces noise onboard the vessel, the surrounded area and the neighbourhood (Port of Helsinki, 2015), and underwater.

As explained in the previous paragraph, the stoppage in using ships' diesel generators in ports has an immediate impact of mitigation of the air pollution and UWN radiation, and also reduces the formation of fouling on the ships, leading to a further mitigating effect during the ship's sailing. It will also reduce the risk of introducing invasive species to the environment. Further study of the topic can elaborate more on the benefits of cold ironing.

5.2.4 Incentive Measures

Gaps and barriers exist in utilizing technologies and operational procedures. Investment cost, technology, uncertainty, split incentive, safety issues, and reliability are some of the gaps that can be named (Acciaro, Hoffmann and Eide, 2013). Design optimization in ship's hull and propeller, insulating the engine and refitting or considering operational measures such as reducing speed to less than Cavitation Inception Speed (CIS), hull and propeller maintenance, rerouting and using technologies to reduce noise are some actions that can be considered to mitigate UWN pollution (IMO-MEPC, 2013).

Although all are costly and affect the financial benefit of the companies, creating incentive by giving a good discount on the port dues and operation costs in port can encourage companies to utilize mitigating measures. This also can aid in reducing any potential or existing gaps.

In 2007, the Vancouver Fraser Port Authority (VFPA) through its Eco Action gave support and incentives (discounts on port dues) to vessels that had a variety of fuel, technology and environmental management practices, to introduce fewer emissions to the port of Vancouver. Meanwhile, in 2017 the Port of Vancouver considered extending this incentive to quieter ships (port Vancouver, 2018), and making Canada one of the pioneer countries with an incentive in respect of quieter ships. Ships may qualify for gold, silver or bronze levels by voluntarily meeting industry best practices.

The conditions required to be placed in the Gold, Silver, or Bronze ranking are explained in the Vancouver Fraser Port Authority POV-FEE Document (2018). In accordance with the mentioned document, many program areas are declared in respect of each ranking rate. Most of the requirements concern air emission. In the Gold ranking, quiet vessel notations from 3 classifications Bureau Veritas, DNV-GL, and RINA are only directly related to the noise mitigation. However, shore power and alternative fuel (Natural gas, biodiesel), which are considered as belonging to the air emission program, are also effective in reducing noise. In the silver rating, there are no program areas for reducing underwater noise directly, but alternative fuel, which is classified under air emission, can be effective in reducing noise too. In the Bronze ranking, in addition to alternative fuels, which has an effect on noise reduction, propeller modification to reduce cavitation and improve wake flow is considered as a direct program area for reducing underwater noise.

In accordance with Ligtelijn et al. (2014), a significant reduction (5-20dB) in noise is possible for most kinds of the ship with relatively low cost and without major innovation. Although some ship owners feel responsible for taking action to address environmental issues, more owners will become enthusiastic if the proposed solutions do not create a cost burden on the ship owners or if any related cost is compensated by increasing efficiency and lowering fuel consumption. This policy was conducted in respect of Chapter 4 (Regulations on energy efficiency for ships), Annex VI of The International Convention for the Prevention of Pollution from Ships (MARPOL) and was successful. Although the relationship between efficiency and UWN is still not completely clear and sometimes they are in contrast with each other (especially in propeller aspects), many operations and maintenance are effective in both efficiency and mitigation of underwater noise simultaneously.

In 2011 the Energy Efficiency Design (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) were introduced to new and existing ships (IMO-MEPC, 2011). The EEDI considers continuous technical and design developments in respect of ships to improve energy efficiency in new ships. However, the SEEMP is the only available international regulatory instrument (Johnson et al., 2013) for improving ship efficiency through better management and implementation of best practice (Conducting the SEEMP onboard is not compulsory) (Register, 2011). Moreover, as per IMO-MEPC, (2014), the design and operational measures are two ways of reducing noise propagation, and also as measures for improving energy efficiency (EEDI for design, and SEEMP for operational measures). Meanwhile, due to the cost efficiency of energy efficiency through reducing fuel consumption, shipowners are eager to comply with the regulation. Consequently, it is suggested that a policy in respect of UNW radiation be set following the trend of energy efficiency, EEDI, and SEEMP to achieve more success in encouraging ship owners to collaborate in reducing UWN pollution. The technologies, initiatives and measures in EEDI and SEEMP can not only improve energy efficiency, but also mitigate UWN. However, there is a need for further study to discover the relationship between the energy efficiency and UWN mitigation of each technology, which should be considered in EEDI, and SEEMP. In the long term, after evaluating the relationship of each technique and operational measure in both energy efficiency and UWN radiation, their relationship can be linked to EEDI and SEEMP measures.

In this part, it is suggested to apply the incentives in the Port of Vancouver, based on the techniques and operational measures that can mitigate both air emissions and UWN pollution simultaneously. The port of Vancouver can propose a recommended EEDI and SEEMP for different types of vessels and those that comply with them can enjoy the presented incentives. However, a comprehensive study is required to determine and introduce the proper techniques and operational measures for different types of vessels and dedicate the incentives on this basis.

Chapter 6

6. Conclusion and Recommendations

The UWN is an important environmental issue which has a negative effect on sustainable development. Due to shipping growth (ship size, number of fleets, and longer distances), if a proper mitigative action has not been taken in ample time, the negative externalities of UWN pollution from commercial vessels can become more serious in future.

In contrast to the many other types of ship pollution, UWN is not visible to humans. It is necessary to make it visible through a scientific approach and collection of data on its negative impacts and effects. Creating sensitive area charts and plans in respect of UWN pollution and vulnerable marine species can assist any further decision making. Identifying the effects of UWN pollution on economic and business aspects can provide a good motivation for considering UWN as an issue. Also, linking UWN pollution to the UNSDGs goals in collaboration with other organizations such as the Food and Agriculture Organization (FAO) can produce a driver and trend toward international regulations such as EEDI and SEEMP to remove the present international legal gap pertaining to UWN pollution. Figure 6.1 demonstrates the proposed general trend and drivers for UWN pollution adapted from Ölcer et al. (2018) to incorporate the UWN regulation for IMO to consider.

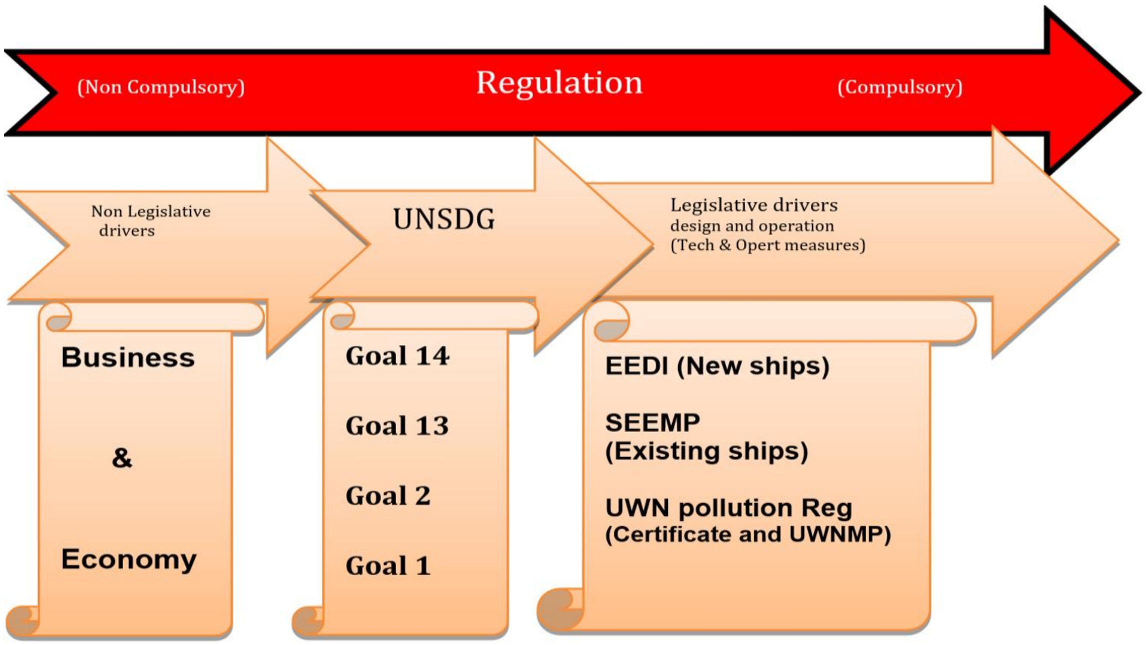


Fig 6.1. The suggested trend to regulate UWN pollution.
Source: Adapted from (Ölcer et al., 2018)

There is a great potential in EEDI and SEEMP to improve both efficiency and decay of UWN radiation. Although there is a reverse relationship in respect of propeller efficiency and UWN radiation, and the related solutions given are at the conceptual level, there are many other design aspects such as improving the design of the machinery and hull and its interaction with the propeller, which can improve efficiency and mitigate UWN radiation simultaneously. Moreover, many operational measures such as slow steaming, just in time, hull and propeller cleaning and maintenance, which are recommended in the SEEMP to increase efficiency, can mitigate UWN radiation too. This potential and capacity in the EEDI and SEEMP can be considered as a basis for establishing incentives for ports to mitigate both emissions and UWN simultaneously. Moreover, when the stakeholders are aware that the mitigation measures for UWN pollution have payback by reducing fuel consumption, they become more enthusiastic in utilizing those measures.

Correct decisions at the early stages of design are very important. By combination and utilizing both CFD and EFD technologies, the probable noise radiation and the effect of different mitigation measures can be determined. This will help in analyzing their interaction as a system, and selecting the best ones to utilize. By this method, the optimized type of machinery, engine room, and propeller (suitable propeller with respect to the ships type and its interaction with the ship's hull) can be identified in the early stages of design.

Moreover, lessons can be learnt from other types of ships that have less UWN radiation due to the nature of their work, such as navy and research vessels. Those lessons can be adopted for the nature of the commercial vessels as an effective step in mitigation of UWN pollution.

While more concentration has been paid to reducing UWN from the source of the noise (i.e. design, retrofitting, hull and propeller cleaning, and slow steaming) and reducing the level of received noise (i.e. by rerouting and convoy), no attention has been paid to reducing and buffering the noise between the source and the receiver. There is a great potential to mitigate the noise between the source and receiver. It is necessary to investigate and innovate the technologies that can act as a buffer and noise absorber between the noise producer and the receiver, such as the air bubble curtain. However, it needs further study and adoption for the open sea.

Furthermore, the methods to reduce UWN radiation during ships' (UN) berthing operations and during port stay, such as cold ironing, can be a great step to mitigate both UWN and emissions simultaneously. Further study is suggested to develop and innovate new technologies and operational measures to mitigate noise in port.

Since UWN pollution is a new issue in comparison to other types of marine pollution, there is a lack of sufficient awareness among people in society. More information and awareness are necessary not only for society but also among marine stakeholders to raise their awareness. The role of the media and the social networks should not be underestimated. Moreover, considering UWN mitigation as a part of the action from the stakeholders in their Corporate Social Responsibility (CSR) reports can educate and encourage other stakeholders to take proper and ample actions accordingly. Moreover, if the personnel onboard are aware of UWN pollution and its negative impacts and if their mindset to consider the issue as an important type of pollution, more success can be achieved in mitigation of noise in operational measures. In this respect, the marine colleges and universities, such as the World Maritime University (WMU), can play an important role. Further study in the role of the human element in reducing UWN pollution can be an interesting topic.

Besides the awareness of crew onboard, the master should be provided with sufficient information about the UWN radiation of the vessel and proper actions which (s) he can take accordingly. If the amount of UWN radiation shows onboard the vessel on any system such as ECDIS and is recorded properly, the master, by comparing the amounts with the provided information for that individual vessel, can identify any abnormalities and can take appropriate actions in ample time.

Furthermore, the master should be provided with sufficient information and assistance to make the proper decision in trade-off between efficiency and UWN with consideration of the safety of operations. For example, in CPP vessels, in addition to the shaft speed and propeller pitch program, if the amount of UWN radiation is provided for each condition, the master, with consideration of the safety of navigation, can use the appropriate shaft speed and propeller pitch, with minimum UWN radiation.

Figure 6.2 shows the suggested general trend to address UWN pollution from commercial vessels. The Figures consist of three colors: orange, blue, and green.
The orange one is related to the first step as explained before. By identifying the negative impacts of UWN pollution on commercial and economic aspects, motivation and required drivers can be created for mitigation of pollution. In the next step, the linkage of the UNSDGs and UWN pollution should be elaborated to improve and develop sustainable shipping. As explained in Chapter 2, UWN pollution has a direct link to Goals 1, 2, and 14, and indirectly linked to Goal 13. Meanwhile, this will help in collecting data and creating noise maps for sensitive areas. The next step is adopting and identifying the EEDI and SEEMP measures that can help to mitigate UWN pollution and emissions simultaneously. In addition, Research & Development (R&D) studies can

introduce new ship designs, technologies and operational measures. However, their effects should be proven by CFD and EFD technologies before they are utilized in order to make the actions more effective and prevent any additional cost burdens.

The next step shown by the blue line is related to the achievements of the SEEMP and EEDI. Setting a benchmark for UWN radiation for different types vessels, improving the ship's hull and propeller design and their interaction in order to mitigate emissions and UWN radiation from vessels can be achieved through the EEDI. At the same time, the operational measures and effect of slow steaming in reducing UWN pollution and emissions for different types vessels can be determined.

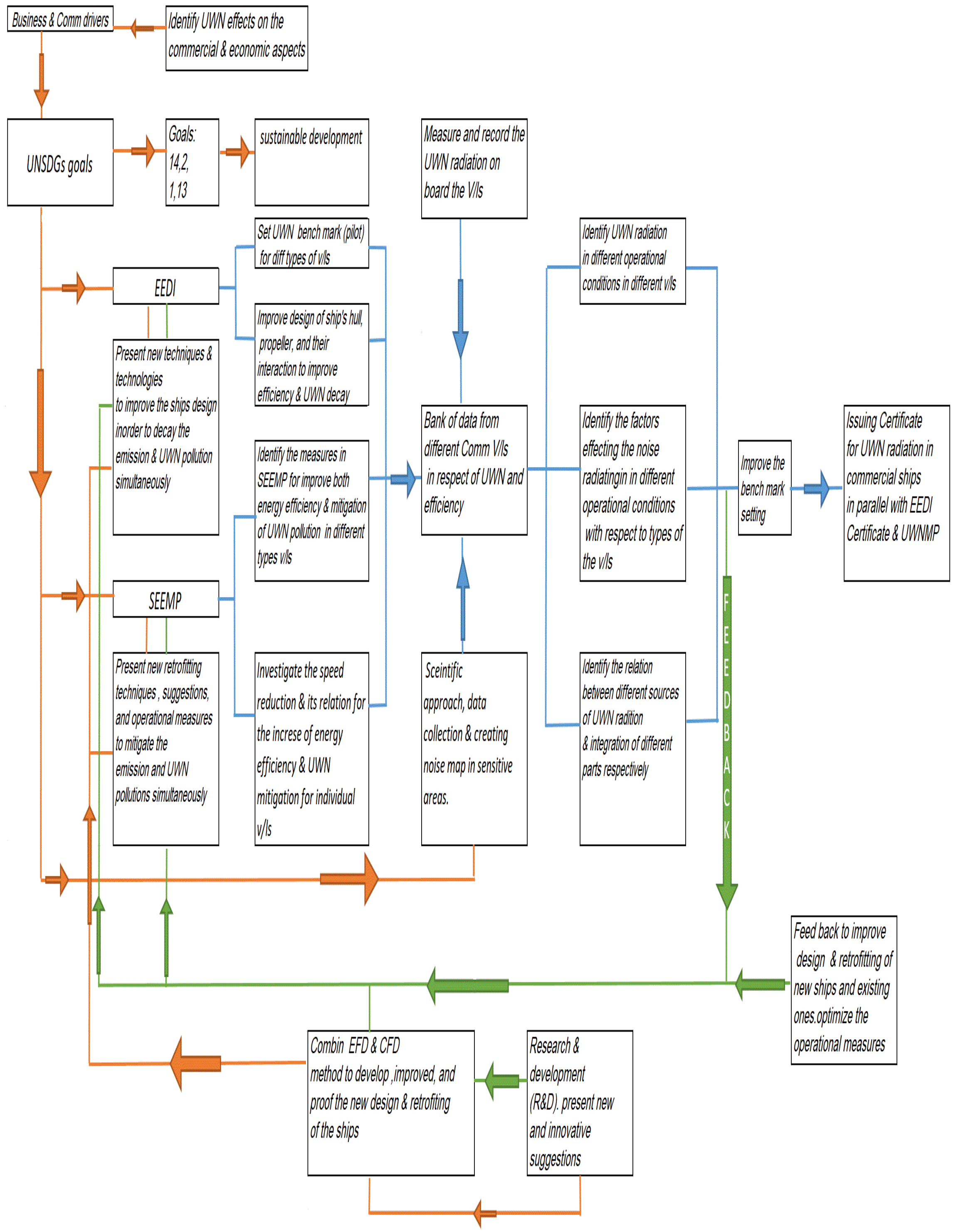


Fig 6.2. The suggested general trend to address the UWN pollution.

In other steps, it requires UWN radiation from different vessels in different operational conditions to be measured and recorded. It is necessary for the vessels to be equipped with a device which indicates the UWN and records the results accordingly.
The results of these activities will create a bank of data from different vessels in different operational conditions in respect of UWN radiation and efficiency. By analyzing the created data bank, the following information will be achieved;

- Identify the amount of UWN radiation in various operational conditions in different types of the vessels;
- Identify the factors which can affect UWN radiation in different operational conditions with respect to the types of vessels;
- Identify the relationship between different sources of UWN radiation and the integration of different parts in different types of vessels.

This will help to set a proper benchmark for different types of vessels.
Moreover, the feedback (green line) from these procedures will create a Plan, Do, Check, Act cycle (PDCA cycle), which is continual and will improve the design, retrofitting, and operational measures to adopt a benchmark with the advent of new technologies, techniques, and operational measures. As explained before, R&D and proving the effects of this new suggestion by EFD and CFD technologies is crucial to making the procedure more cost-effective.
In the end, this cycle can lead to providing and issuing a certificate for UWN pollution for vessels in parallel with the EEDI certificate or creating an Under Water Noise Management Plan (UWNMP) for each individual vessel. However, this is an ambitious and long-term goal and requires clarification of all aspects of UWN pollution for all stakeholders and a comprehensive study.
The last but not the least is related to the importance of trade-off between different attributes in addressing the issue. This study shows that to tackle UWN pollution a trade-off between the three pillars of sustainable development (Social, Economic, and Environment) is required along with the necessity of replacing single dimensional thinking with multi-dimensional thinking.

The trade-off will allow the solution to be modified and tailored to any other similar case in other parts of the world by changing and updating the number of attributes and their weight, depending on the decision-makers' preferences.

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