Development of Decision Support Tool for Advising on Selecting Ballast Water Treatment System

By

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Abstracts

In general, for shipping companies or any organisation the important decisions are made to deal with the selection of a particular alterative. This thesis presents a decision support tool for selecting a Ballast Water Treatment System (BWTS) for a given ship. A single decision has to be made between a number of given BWTS alternatives for a VLCC tanker under its voyage in the presence of a single decision maker.

The decision support tool was developed using the Analytical Hierarchy Process (AHP) method, in order to help decision makers in shipping companies to select the most feasible BWTS for their ships. The ultimate aim of the developed decision support tool is to aid decision makers in shipping companies to make the right decisions when selecting between numbers of BWTS alternatives for their ships.

In order to achieve the aim of this thesis several objectives were identified as follows: (1) To identify the influencing parameters and/or criteria related to both ballast water treatment system and ships parameters; (2) To evaluate the importance of the selected criteria for both BWTS and ship parameters/criteria; (3) To apply an appropriate Multi-Criteria Decision Making (MCDM) technique along with the above points; (4) To validate the develop decision support tool and investigate its applicability in actual case studies.

The criteria were identified through the literature review and the semi-structured interviews with twelve senior staff or experts from three different trade shipping companies. The latter was an important step in finalising the new decision support tool, to evaluate the importance of the selection issues in shipping companies, and to evaluate the importance of the criteria used by the developed model. In addition, it helped framing the hierarchy structure of the Analytical Hierarchy Process (AHP) as a new model to support the selection of BWTS for ships. The comparisons between the case study, derived results, sensitivity analysis, robustness test, case study two and the validation interview with two experts from a well-known shipping company have supported the applicability and the validity of the model to help decision makers in shipping companies to select the most feasible BWTS for their ships. The model has also demonstrated its ability to aid decision makers or researchers in understanding the relationships between the different processes and their consequences on their BWTS selection.

Declaration

This thesis is a result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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The work invested in preparing this PhD thesis was carried out at the University of Strathclyde during the years 2013-2015. A lesson learned from the previous experience before joining University of Strathclyde taught me to become a stronger person who is able to achieve his dreams. I thank Allah and his Last Prophet Mohammed (peace upon him and his holly progeny and pious companions) for blessing me with this opportunity and ability to finish what I've started before coming to University of Strathclyde.

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I also owe enormous gratitude to my supervisors, Dr Theotokatos (Makis), Professor Turan and Professor Belton for their encouraging way of guiding me to a deeper understanding, patient guidance, encouragement and knowledge about my field of work. I have been extremely lucky to have you as my supervisors who cared and responded to my inquiries, full supervisory meetings requests which I never experienced before coming to Strathclyde University. If I had experienced the same style of supervision, I would have finished this PhD 2 years earlier.

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List of Abbreviations

BWTS	Ballast Water Treatment System
VLCC	very large crude oil carrier
AHP	Analytical Hierarchy Process
MCDM	Multi-Criteria Decision Making
NO	Nitrogen Oxides
SO	Sulphuric Oxides
IMO	International Maritime Organisation
BWM Convention	International Convention for the Control and Management of Ship's Ballast Water and Sediment
MAV or MAU theory	Multi-Attribute Value (or utility) theory
FAHP	Fuzzy Analytic Hierarchy Process
Globallast	Global Ballast Water Management Programme
BWM	Ballast water management
SOLAS	Safety of life at sea
DBT	double bottom tanks
ST	side tanks
WT	wing tanks
FPT	for peak tank
APT	after peak tank
TST	topside tanks or upper wing tanks
CT	central tanks
RO-RO	Roll-on/roll-off ships
DWT or dwt	deadweight
USA	United States of America
MEPC	Marine Environmental Protection Committee
UNCED	United Nations Conference on Environment and Development
BWWG	Ballast Water Working Group
FPSO	Floating Production Storage and Offloading
cfu	colony forming unit
gt	gross tonnes
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
USCG	United States Coast Guard
NANPCA	Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990
NISA	National Invasive Species Act of 1996
EPA	Environmental Protection Agency
COTP	Captain of the Port
BWMS	ballast water management system
CFR	Code of Federal Regulations
AMS	Alternative Management System
NBOB	No ballast on-board
MBW	Minimal Ballast Water
UV	Ultraviolet irradiation
SRC	shipbuilding research centre
NOBS	no ballast water ship

MIBS	minimal ballast water ship
WMU	World Maritime University
DNV	Det Norske Veritas
BWE	ballast water exchange
VLP	Virus-Like Particle
DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
PSA	Pressure Swing Absorption
LNG	Liquefied Nitrogen Generator
VOS	Venture Oxygen Stripping
DO	dissolved oxygen
PIL	Pulse intense light
DBP	disinfection by-product
TRO	Total Residual Oxidant
TBT	tributyltin
LNG	liquefied natural gas
LPG	liquefied petroleum gas
COA	Contract of Affreightment
GLBTDP	Great Lakes Ballast Technology Demonstration Project
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
NPV	Net Present Value
MBTI	Myers-Brigges Type Indicator
FSAHP	Fuzzy-Stochastic Analytical Hierarchy Process
PSC	Port State Control
G-FAHP	Generic Fuzzy Analytic Hierarchy Process
INSC	installation cost
OPEX	operational expenses
MCDA	Multi-Criteria Decision Analysis
QFD	quality function deployment
OTC	Oil Tanker Company
MMT	million metric ton
LPG	liquefied petroleum gas
FNBPG	Fleet New Building Projects Group
FEG	Fleet Engineering Group
MFD	Marine Fleet Department
BCC	Bulk Carrier Company
SGG	Stripping Gas Generator
P-V (Breaker & Valve)	pressure volume
PLC	programmable logic controller
OIT	operator interface terminal
AMS	Alternative Management System
MPUV lamps	medium-pressure ultraviolet lamps

PV	present value
CR	consistency ratio
CI	Consistency Index
TOC	Total organic carbon

List of Publications

- ALHABABI, H. H. M. H., THEOTOKATOS, G. & TURAN, O. 2014a. Analytical Hierarchy Process for matching a ballast water treatment-VLCC Marine and Offshore Engineering Technology Conference MOETC. Kuwait.
- ALHABABI, H. H. M. H., THEOTOKATOS, G., TURAN, O. & BELTON, V. 2014b. A Novel AHP Model for Selecting the Most Feasible Ballast Water Treatment for a Bulk Carrier International Conference on Maritime Technology ICMT. GLASGOW, UK.

Chapter 1: Introduction

1.1 Background and the motivation of the study

Shipping is recognized as one of the most economical and cost effective mode of transport system. Comparisons by different researchers of all transportation modes have concluded that shipping is more economical and cost effective, in terms of value per volume and weight, than either overland or air transport (Stopford, 2009b). Another reason for the favouring of shipping transport above the other modes is the fact that two-thirds of the world's surface is covered by water (ICS, 2005b). Therefore, even the parallel development of other transport modes such as railways could not compete with ships over long distances (Buxton, 1987). This has been shown by the recent approximation of 80 per cent of goods traded internationally are carried by sea (UNCTAD, 2010). Therefore, shipping has played and still plays as the heart of the globalisation which is the remarkable growth in international trade and exchange.

However, the gradual and fundamental changes i.e. environmental, social, economic, regulation, stakeholders, political, technological, design etc. have impacted on this mode of transport as risks and uncertainties. For example, ships are designed to interact with their surrounding environment and that has turned shipping into a global pollution contributors either intentionally or not (e.g. noxious emissions such as Nitrogen Oxides (NO) and Sulphuric Oxides (SO), and Ballast Water contented with bio invasion threat) that has been linked to a variety of public health problems, economic impacts etc.

Several studies such as (Molnar et al., 2008, Williams et al., 1988, David et al., 2007) have identified that shipping activities, specifically ship's ballast water, are the key vectors of all the bio-invasion. "*Bio-invasion occurs when the natural barriers (such as land locks, changes in water temperature and quality or salinities) cannot prevent the dispersal of native aquatic organisms when carried in ship's ballast water (or attached ship's hull)*" (Pazouki, 2012). These organisms which survive the ship's voyage may establish themselves, in the absence of predators, in the new receiving location and results in uncontrolled impacts (e.g. economic, ecological and health). Bio-invasions related to ship's ballast water have been identified as one of the four greatest threats to the world's oceans (IMO, 2013, Sassi et al., 2005); the other three are land-based sources of marine pollution, overexploitation of living marine resources and the physical alteration/destruction of marine habitat.

As a result, to eliminate and minimise risks of bio-invasions, in February 2004 the international Convention for the Control and Management of Ship's Ballast Water and Sediment (named BWM Convention in this thesis) was adopted with 14 guidelines in order to prevent, minimise and ultimately eliminate bio-invasions caused by shipping activities. Consequently, this convention requires all the commercial ships to comply with IMO regulations by implementing a ballast water management system that meets the IMO Regulations and particularly B-3 regulation under the specifically named D-2 discharge standards.

Until today, many manufacturers and ballast water treatment vendors adopted various ways of water treatments in order to treat ships ballast water to comply with IMO standard D-2 of the BWM Convention. As a result, today, there are various types of Ballast Water Treatment Systems (BWTS) in the market claimed that their systems to be effective in meeting the IMO BWM Convention. The problem, which every ship is confronting, is that these systems varied in their approaches to eliminate the harmful aquatic organisms, their environmental risks, cost, processing time, capacity, biological efficacy (named bio-efficacy in this thesis), etc. These variations have made the selection of BWTS such a complex decision making issue facing all shipping companies and operators. Shipping companies as any other organisation will always deal with the selection problems. In this situation, shipping companies need to choose at least one single BWTS alternative which best fits to their strategic objectives. It is worth noting that, some of these decisions may be strategic decisions because they can affect the company in long period. Therefore, evaluating and selecting the most appropriate BWTS alternative is an important task that shipping companies must carefully take into account. It is no longer possible to ignore the fact that real decisions are a result of a compromise or trade-off to choose the most appropriate alternative that can best satisfy all the important criteria. As a result, it is important to apply the Multi-Criteria Decision Making (MCDM) techniques, in order to evaluate the most appropriate alternative which can satisfy the stakeholder criteria.

Several studies such as (Mamlook et al., 2008, Blanco-Davis and Zhou, 2014, Jing et al., 2013) have investigated the problem associated with the comparison and then the selection of the best BWTS alternatives. However they varied both in their approaches and the chosen criteria for comparing between the different BWTS alternatives. Although various studies investigated the problem associated with the comparison and the selection between BWTS in the literature, there have been few or limited studies investigating the feasibility of incorporating ship related criteria in their models for selecting the most feasible BWTS alternatives. In addition shipping companies or operators have been neglected or not sufficiently considered in the previous studies. Based on the identified gap in the literature, therefore, the aim of this thesis is defined to fill the gap in the literature.

1.2 Research aim

The aim of this thesis is to develop a decision support tool or model to aid decision makers (e.g. shipping companies/operators) to select the most feasible BWTS for their ships. In order to achieve this aim, the specific objectives of this research are:

1. To identify the influencing parameters and/or criteria related to both ballast water treatment system and ships parameters.
2. To evaluate the importance of the selected criteria for both BWTS and ship parameters /criteria.
3. To apply an appropriate Multi-Criteria Decision Making (MCDM) technique along with the above points.
4. To validate the developed decision support tool and investigate its applicability in actual case studies.

1.3 Thesis structure

The thesis consists of eight main chapters and the associated appendices. The content of each chapter is given as follows:

- **Chapter 1**: Provide an overview of the research study background and motivation, clearly defining the aim, the objectives, and the structure of this thesis.
- **Chapter 2:** This chapter presents an overview on ship's ballast water, marine vehicles and the relevant studies of the selection of the best ballast water treatment system. In this chapter the gaps has been identified and the problem statement has been discussed leading to the aim of this thesis and the objectives that need to be achieved.
- **Chapter 3**: This chapter provides an account of the author's considerations with regard to the selection of the appropriate methodology and the overall research design for this study. This chapter considers the different elements about research

methodology, paradigm (qualitative or quantitative or both) and researcher's assumptions. Then it argues the consideration and methodology employed in this study. Two most popular MCDM i.e. Multi-Attribute Value (or utility) theory and The Analytical Hierarchy Process (AHP) were compared and thus selected AHP as an appropriate MCDM method in this study.

- **Chapter 4:** This chapter provides the first data collection and analysis process and a detailed overview of the case study with 12 experts interviews from three leading different trade shipping companies. The issues of the ballast water, the importance of the selected criteria, the lack of existing decision tool in shipping companies, and the amended structure of the developed model which has been slightly modified, are discussed and presented in this chapter.
- **Chapter 5**: This chapter focuses on how the research method is applied into actual case study. The data collection and evaluation based on actual data requirement for the developed model, are discussed. In this chapter, three sources of data were needed namely: data of a ship and her voyage; technical parameters for each of the selected Ballast Water Treatment Systems (BWTS) alternatives; and decision maker evaluations for the relative importance of each identified criteria in the decision support tool. Details on the needed information collection and evaluation are presented and discussed in this chapter.
- **Chapter 6**: This chapter presents details on the outcome or the results from the decision tool based on the input data acquired from Chapter 5. In this chapter, there were no surprises experienced and the outcome of the model was found intuitively acceptable. However, due to many uncertainties of the inputs data, more analysis and investigation were required for the applicability and the validity of the model.
- **Chapter 7**: This chapter can be considered as the validation chapter. The sensitivity analysis of the developed model was performed to validate the applicability and the sensitivity of the model to the changes of the priorities of each criterion. Ship compatibility criterion was found as the most critical criterion which may, with little possibility, alter the selected alternative. Based on the latter information, two robustness tests were put forward in order to validate the applicability of the model. In order to test the latter, case study two were developed by changing the voyage duration and trade route of the VLCC in order to test whether this would alter the

decision on the selected alternative or not. This chapter also argued the validity of the proposed model and the outcome by answering three important questions:

  - Why the methodology used in this thesis is valid?
  - Why the developed model is valid?
  - Why the outcome of the model is valid?

- **Chapter 8**: This chapter is considered as the conclusion of this thesis. It also provides a summary of the approach adopted in this research, presents the accomplishment of the research process, and describes where aims are achieved. In addition, the thesis contribution was presented; the limitations which were encountered during the time of this research and recommendations for future research are discussed.

In addition the following appendices are provided:

- **Appendix-A**: The questionnaire used to interview experts for the purpose of this study is presented.
- **Appendix B**: The survey named ‘criteria weighting questionnaire’ is attached.
- **Appendix C:** The validation’s questions of the interview are presented.
- **Appendix D:** AHP analysis and the implementation in Microsoft Excel are presented in detail.
- **Appendix E:** The Fuzzy Analytic Hierarchy Process (FAHP) application study to the 1st model is presented.

Chapter 2: Overview on Ship’s Ballast Water, Marine Vehicles, and Selection of the best BWTS alternatives

2.1 Ship’s Ballast Water

2.1.1 Definitions

It is important to highlight small but significant terms used in this study such as **‘Ballast’, ‘Ballast Water’, ‘Ballast water management ’**, **‘Ballast Water Treatment System’, ‘Harmful aquatic organisms and pathogens’ and ‘Ballast water system’**.

According to the Global Ballast Water Management Programme (Globallast) partners, the word **‘Ballast’** defined: *“Any material used to weight and/or balance an object. One example is the sandbags carried on conventional hot-air balloons, which can be discarded to lighten the balloon’s load, allowing it to ascend”*(GloBallast, 2013).

‘Ballast Water’ defined as: *“the water with its suspended matter taken on board a ship to control trim ,list, draught, stability or stresses of the ship”*(IMO, 2009).

‘Ballast water management’ (BWM), according to IMO (2009): *“is the mechanical, physical, chemical and biological processes, either singularly or in combination to remove, render harmless, or avoid the uptake of harmful aquatic organisms and pathogens within ballast water and sediments”*(IMO, 2009). In other words, any action or design taken to minimise, eliminate or avoid the uptake of the harmful aquatic organisms and pathogens within ship’s ballast water can be named as ballast water management such as free ballast ship design, using ballast water for desalinations or any other concepts related to avoiding the uptake of the harmful aquatic organisms. Therefore, a ‘**Ballast Water Treatment System’ (BWTS)** can be seen as a small part solution to the BWM.

"Harmful aquatic organisms and pathogens" , according to IMO (2009), is defined as: "*aquatic organisms or pathogens which, if introduced into the sea, including estuaries, into freshwater courses, may create hazards to environment, human health, property or resources, impair biological diversity or interfere with other legitimate uses of such areas"* (IMO, 2009).

'**Ballast water system'** is an important and specifically designed system to allow a ship to empty or fill their seawater tanks in order to control trim, list, draught, stability or stresses of the ship. Ballast water systems will be discussed next section.

2.1.2 Ship's ballast water system

Historically, ships have carried solid ballast, in the form of rocks, sand or metal, for thousands of years (GloBallast, 2013). However, today, most of the seagoing commercial ships use sea water as ballast water. This is because it was much easier to manage by loading on and off a ship, and therefore more efficient and economical than solid ballast, whenever is required.

Ships are very complex vehicles which were built to operate in a very corrosive and humid environment for long period of times with a high degree of reliability (Taylor, 1996). The purpose of each built ship differs from one type to other type of ships even between sister ships which were built for different purpose, and routes may also vary.

A ship can be viewed as a three compartments: the cargo carrying compartment, the accommodation and the machinery compartment, which will vary in their sizes depending on the type of ship (Taylor, 1996). The purpose of the ship can influence the size proportion between these compartments. For example, conventional oil tanker will have small accommodation compartment with several cargo carrying tanks divided by longitudinal bulkheads and several transverse bulkheads. Unlike tankers, a passenger ship will have large accommodation compartment, since this is the ultimate purpose of this kind of ship.

Within any ship there are many sophisticated precisely designed systems. Major ship's systems such as: the cargo pumping room, firefighting system, sewage system, jacket water system, sanitary system, steam boiler system, boiler feed system, laundry system, air conditioning/ventilation system , fuel oil system, lube oil system, bilge system, and ballast water system. It is important to note that depending on the capacity and the ship type, each of these systems may comprise various items and different types of piping, piping's lengths, pump types, pump capacities, valves type, various size and shapes of ballast tanks, ballast tanks' locations, which a marine engineer must be familiar with each system from one end to the other, knowing the locations and the use of every single valve on-board his ship.

Each of these systems has its particular duty and purpose, and they vary in their importance to the ultimate goal which is running a ship efficiently and safely. For example, we cannot afford to lose the fuel system to the main engines (not even for few minutes) because that will shut off our main engine or boiler and may cause accidents (worst case scenario) as the ship will not be able to manoeuvre, while it might be fine to lose the ventilation or laundry for some time, depending on the location and type of ship indeed.

2.1.2.1 The impotence of the ballast water system

The ballast water system on board ships has a significant importance which can be summarised, but not limited to, by the following points below (Pazouki, 2012, Enshaei and Mesbahi, 2011, David et al., 2014):

- To achieve their required safe operating conditions under various weathers.
- To achieve structural safety by maintaining the permissible strength limit to avoid structural damage.
- To achieve the required trim (propeller immersion).
- To achieve the required stability of the ship.
- To achieve the optimum speed and avoid bow water emerging in heavy seas.
- To balance the ship and maintain the volume to weight ratio (dynamic forces). Inadequate balance on ship's hull subjects the ships to shear and torsion forces, bending moments, and slamming.
- Some ships require ballast water to adjust their height for the required cargo handling cranes at some ports.
- Reduces stresses of the ship's hull.
- Improves propulsive efficiency by submerging the propeller fully into water.
- Improves manoeuvrability of ships by submerging the rudder fully into water.
- Restores the stability as fresh water and fuel are being consumed during the voyage.
- Satisfy dynamic factors such as weather and sea condition on the route, the approach to shallow waters, and the consumption of fuel during the voyage. For example, ships

would choose to sail heavy ballast condition i.e. maximum ballast loaded when expected bad weather or when need to sail under bridge.

Therefore, the ballast water system is an important system for ships. It is worth noting that pumping seawater will also require pumping the correct amount of ballast water to achieve an even load distribution to the ship hull.

Major components of a ballast water system which varies between the different types of ships are: ballast water pumps, ballast water capacity, sea chest, ballast water tank's shapes and locations, piping and different types and sizes of valves Figure 2-1.

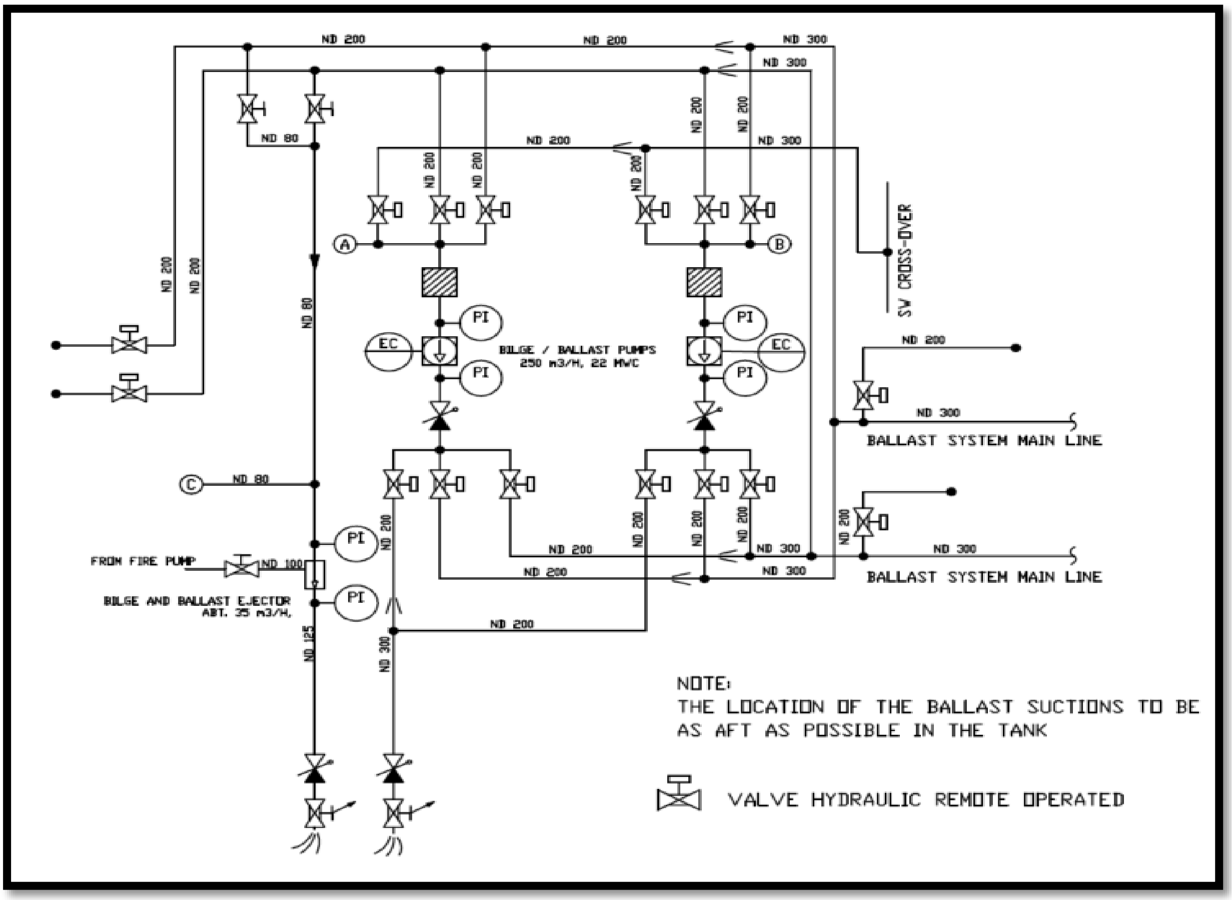


Figure 2-1: Typical bilge/ballast water system (Theotokatos, 2015)

It is worth noting that there are no specific arrangements or regulations that specify or addresses the design and location of these major ballast water components. For example, the ballast water system in Figure 2-1 is shown interconnected with other systems such as bilge and firefighting systems. However, one may find the ballast water system as an independent system with segregated ballast tanks and dedicated ballast pump.

Some ships such as a crude oil carriers or iron ore can be found using their cargo holds for ballast water, which is connected to a very large oily /water separators that have the capacity to reduce oil pollution will be extremely important. However, this type of system may no longer exists because the oily water separator unit aims to treat this oily water in order to remove or minimise oil discharge to 15 parts per millions (ppm) (McGeorge, 1995) rather than disinfecting any organisms and thus with the new IMO convention for ballast water management, it will be very rare, if they ever exists, to have such a system on-board ships unless for emergency purposes. For example, the international convention for Safety of Life At Sea (SOLAS) 1974, forces passenger ships to arrange one ballast water system pump to aid/act as the general circulating pump and also has to have emergency bilge suction (McGeorge, 1995). This is to support the bilge system in case of an emergency situation.

The concept of designing oily/water separators with the ability of treating ballast water has not been considered until today and the author believes that such a concept deserves further attention in future studies.

There is a clear relation between ship's ballast water system, ship type, ship size, ballast tanks volume and size, and the ship's cargo capacity. For example, the ballast tanks can be located in the ship's double bottom (DBT- double bottom tanks), port and starboard along the sides (ST- side tanks or WT- wing tanks), in the bow (FPT- for peak tank), in the stern (APT- after peak tank), port and starboard underneath the main deck (TST- topside tanks or upper wing tanks), and other (e.g., CT- central tanks) (David et al., 2014). It is worth noting that FPT and APT tanks are common on all types of ships and the other types of ballast tanks are not necessarily found in all types of ships Figure 2-2.

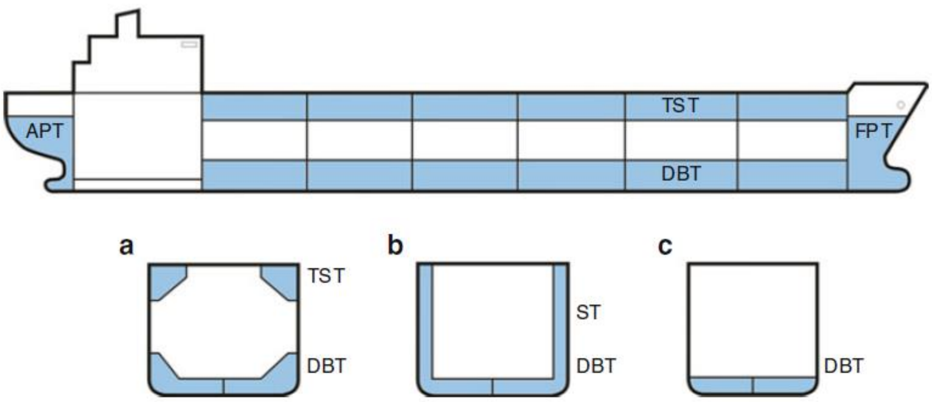


Figure 2-2: Ballast water tanks locations on: (a) most bulk carriers, (b) tankers, containers ships, and some newest bulk carriers, and (c) Ro-Ro and general cargo ships. (APT after peak tank, DBT double bottom tanks, FPT for peak tanks, ST side tanks, TST topside or upper wing tanks) (David et al., 2014).

On other example, ballast water pumping capacity also has clear relationship with the capacity of the cargo pumps Table 2-1. The locations of the ballast tanks, shape and capacity have also clear relationship with ship type and ship's size Figure 2-3.

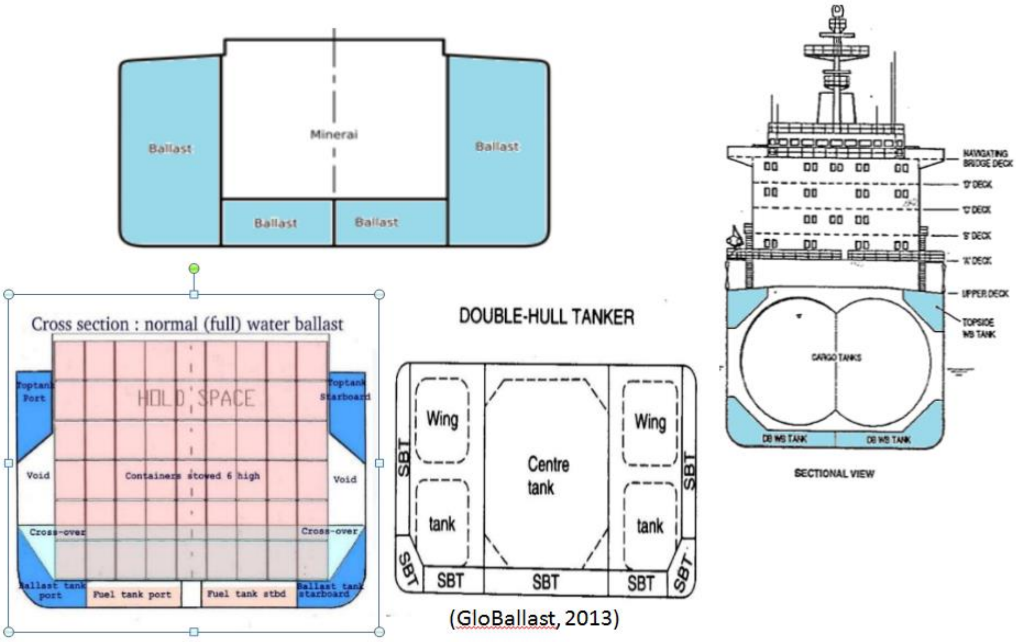


Figure 2-3: Location, size and shapes of ballast water tanks in different types of ships (GloBallast, 2013)

Both Table 2-1 and Figure 2-3 provides clear relationship between the ship's ballast capacities and ship's type which can be determined by ship's cargo capacity i.e. cargo weight and speed of cargo operations. Generally, the more tonnes of cargo a ship can carry, the more ballast may be needed when sailing without cargo on-board (David et al., 2014). In addition, if the cargo operations on a ship are very fast, then the ballast uptake or discharge has to be correspondingly fast.

The ballast capacity of a ship is measured in terms of volume expressed in cubic meters (m^3) and in terms of the ballast pump capacity expressed in m^3 per hour (m^3/h) (David et al., 2014). Therefore, general cargo ships e.g. general cargo, RO-RO, ferries and car carriers, use small quantities of ballast water i.e. 20% to 40% of their deadweight (DWT), whist liquid and bulk carriers e.g. dry cargoes carriers and tankers require significantly larger quantities of ballast water i.e.30% to 50% of their DWT (David et al., 2014).

Generally by law, ships must be equipped with at least two ballast water pumps to ensure that ballast water operations are carried out safely even if one ballast pump is out of order (McGeorge, 1995). The ballast pump capacity is mainly related to the speed of the ship's cargo operations i.e. speed of loading or discharging cargo in a certain period of time. Therefore, bigger ships, i.e. crude oil tankers are the fastest in cargo loading/discharge rates which can reach 10,000 tonnes/h or even faster (David et al., 2014).

On the other hand, ballast water system is not normally connected to the ship's main engines, for cooling purposes, neither has it contributed to its functions. Therefore, from an economic point of view, one may think that the ballast water which is carried on board ships today as wasted cargo only carried from one end of the voyage to the other without any economic value for all these years. Therefore, the concept of adding value to this waste cargo i.e. the ballast water, has not been considered until today and the author believes that such a concept deserves further attention in future studies.

Table 2-1: Estimated ballast water pumping rates (m3/h) (Source: adopted from GloBallast (2013)

Ship Type	Typical pumping rates (m^3/h)
Dry bulk carriers	5,000 - 10,000
Ore carriers	10,000
Tankers	5,000 - 20,000
Liquefied gas carriers	5,000 - 10,000
Oil bulk ore carriers	10,000 – 15,000
Container ships	1,000 – 2,000
Ferries	200 - 500
General cargo ships	1,000 – 2,000
Passenger ships	200 - 500
Roll-on, roll-off ships	1,000 – 2,000
Fishing ships	50
Fish factory ships	500
Military ships	50 - 100
Float-on, float-off ships	10,000 – 15,000
Heavy lift ships	5,000
Military amphibious assault ships	5,000
Barge-carrying cargo ships	1,000 – 2,000

2.1.2.2 Ballast water operation on board ships

Ballast water operation is conventionally performed in the port through ballasting and de-ballasting operation during the ship's voyage. For example, when a ship is empting her cargo, it requires to use the ballast water system to fill up the ballast tanks with seawater. When the ship is loading cargo this ballast water must be discharged out to satisfy the stability, trim, and structural integrity of the ship Figure 2-4 and Figure 2-5. It is worth noting that, ballasting and de-ballasting may also be performed during the navigation depending on the weather and ship's operations. In real life, ballast operation can vary depending on the types and size of ships.

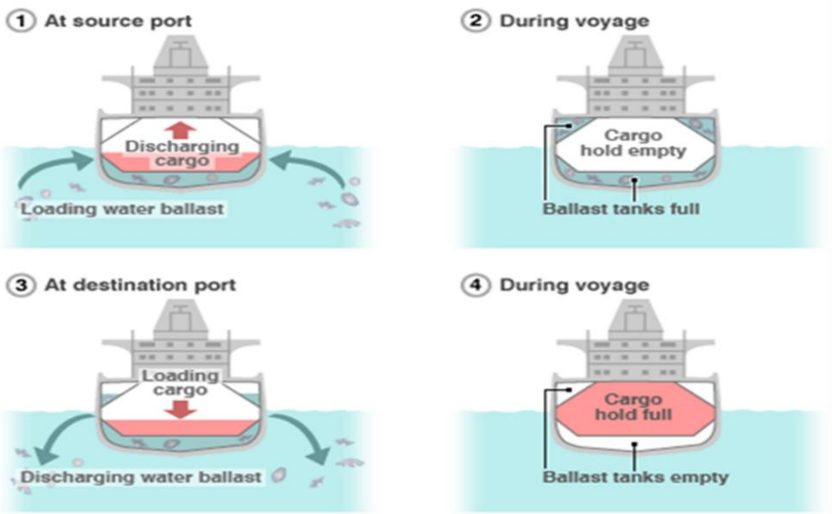


Figure 2-4: ballast water operation most types of ships (GloBallast, 2013)

Figure 2-5: Bulk carrier performing De-ballasting operation at a port in Australia (Source: CSIRO Australia there in (Raaymakers, 2002))

2.1.3 Ship's Ballast water and the Potential Ocean's threat

2.1.3.1 Bio-invasion

Every coast or sea or lake or river in the world consists of its unique native marine creatures. The marine creatures survive in their normal costal environment due to the penetration of sunlight to the seabed and abundance of food and nutrition in their environment. The natural barriers (such as land locks, changes in water temperature and quality or salinities) can prevent the dispersal of these creatures and forces them to remain in their local environment. As a result, a coastal ecosystem is formed where balances between preys and predators are established. However, this balance has been drastically changed due to the interaction of human being with the costal ecosystem such as building large power plants, over fishing, opening canals and land locks, aquaculture, live seafood trading and lately the interaction of shipping activities through ship's ballast water operation in transporting aquatic organisms. Consequently, the balance between these marine creatures and microorganisms started to radically change forming the phenomenon named of bio-invasion.

According to literature, estimates between 3000-7000 different species are moved each day around the globe by ships Figure 2-6 (David et al., 2014).

Figure 2-6: Variety of species found in ballast water samples documenting that also fragile organisms survives the ballasting processes (David et al., 2014).

Scientific research study has also quantitatively identified shipping activity as the most likely vector of these bio-invasions followed by the aquaculture and canal constructions Figure 2-7.

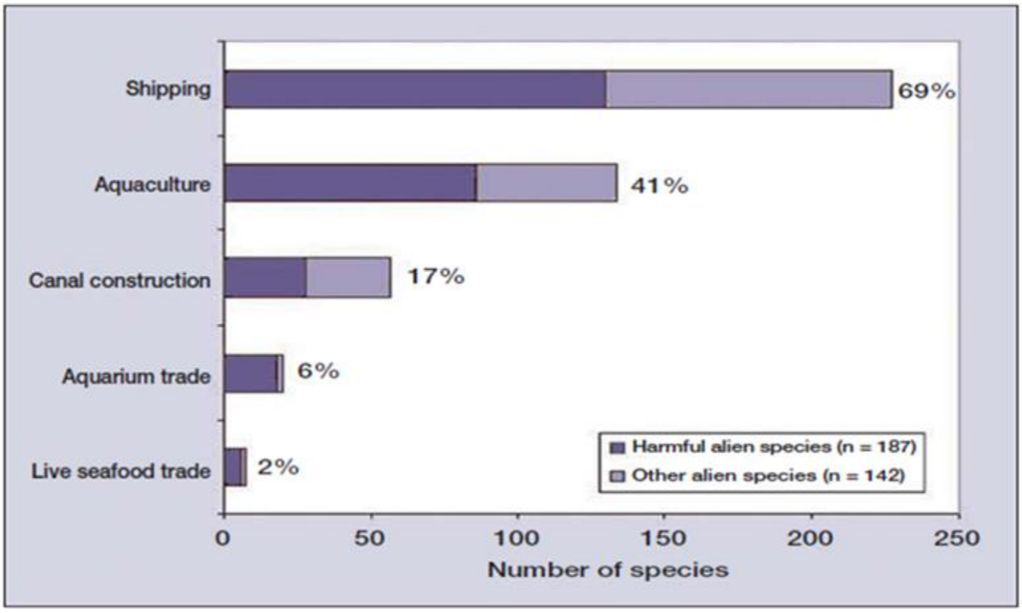


Figure 2-7: Likely number of alien species introduction in percentage (Molnar et al., 2008)

This because once a ship arrives at one destination to load cargo the ballast water must be pumped out of the tanks and into the harbour. As ships routes today cannot be limited to particular region, the risk of the bio-invasions has become under international regulation attention.

Although, some scientific studies demonstrated that most species carried in ship's ballast water will not likely survive the long voyage (Williams et al., 1988). This is due to the harsh environmental conditions inside ballast tanks which can be quite hostile for some organism to survive, nevertheless those who do survive when discharged into the new environment may establish themselves by the absence of predators in the new receiving location (Raaymakers, 2002). Others reasons which support this belief is the development of ever larger and faster ships along with the increased international trade which have facilitated the survival of these species during ship's voyage (Raaymakers, 2002).

2.1.3.2 Potential impacts

According to Raaymakers (2002), bio-invasions caused by ships ballast water impacts are almost impossible to predict. Examples of potential bio-invasion impacts are summarised and divided into three main categories according to (Raaymakers, 2002, Ibrahim and El-naggar, 2012, Tsolaki and Diamadopoulos, 2009):

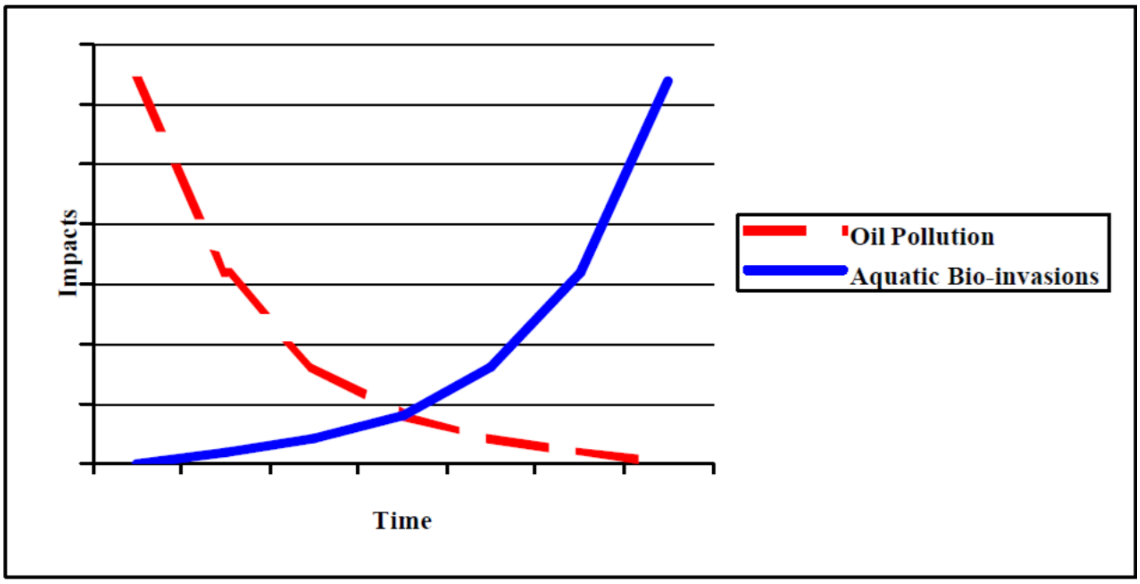
1. **Ecological impacts:**
   - ➢ Competing with native species for space and food.

- ➢ Preying upon native species.
- ➢ Altering habitat.
- ➢ Altering environmental conditions (e.g. increased water clarity due to mass filter-feeding).
- ➢ Altering the food web and the overall ecosystem and displacing native species.
- ➢ Reducing native biodiversity and even causing local extinctions.

2. **Economic impacts**:
   - ➢ Reductions in fisheries production (including collapse of the fishery) due to competition, predation and/or displacement of the fishery species by the invading species and/or through habitat/environmental changes caused by the invading species.
   - ➢ Impacts on aquaculture (including closure of fish-farms), especially from introduced harmful algae blooms.
   - ➢ Physical impacts on coastal infrastructure, facilities and industry, especially by fouling species.
   - ➢ Reduction in the economy and efficiency of shipping due to fouling species.
   - ➢ Impacts and even closure of recreational and tourism beaches and other coastal amenity sites due to invasive species (e.g. physical fouling of beaches and severe odors from harmful algae blooms).
   - ➢ Secondary economic impacts from human health impacts of introduced pathogens and toxic species, including increased monitoring, testing, diagnostic and treatment costs and loss of social productivity due to illness and even death in affected persons.
   - ➢ Secondary economic impacts from ecological impacts and bio-diversity loss.
   - ➢ The costs of responding to the problem, including research and development, monitoring, education, communication, regulation, compliance, management, mitigation and control costs".
   - ➢ It is estimated that the cost of all invasive species exceeds US$138 billion per year in the USA alone.
3. **Human health:**
   - ➢ The introduction of any toxic organisms through ship's ballast water, it may cause diseases and pathogens that may potentially be the causes of illness and even death in humans.

There are many examples of impacts and the types of aquatic organisms found and have been documented in many literatures worldwide. Interested readers may refer, but not limited to, studies such as in (Ferreira et al., 2009, Aldridge et al., 2004, Castilla and Neill, 2009, David and Gollasch, 2008, Jing et al., 2012, DiBacco et al., 2012, Berntzen, 2010, David et al., 2014).

Raaymakers (2002) drew an important comparison between the general features of impacts of bio-invasions verses other sources of ship pollution such as major oil spills Figure 2-8. According to Raaymakers (2002), in a major oil spill accident is likely to occur very quickly and could be catastrophic and acute, but highly visible over time. However, oil spill accident impacts will decrease over time as the oil degrades and cleans up, and rehabilitation activities can be undertaken. On the other hand, in case of bio-invasion, the initial impacts may be non-existent and invisible. However, when the population increases the impacts will increase over time, in an insidious, chronic and irreversible manner. This highlights the significance of the bio-invasion problem if left without doing anything to minimise it or eliminate such a wide and multi direction type of ocean’s threat (ecological, economical & health).



Impacts over time, major oil spill versus aquatic bio-invasions.

Figure 2-8: A representation of comparing between two likely ship activity impacts i.e. oil spill versus bio-invasions over time (Raaymakers, 2002).

2.1.4 Ballast water and the international regulation

2.1.4.1 IMO regulation

As a result of the potential impacts (ecological, economical and public health) of bio-invasion caused by ships ballast water. The first report, about the invasive species in the Great Lakes, was raised to the *International Maritime Organisation (IMO)* through its Marine *Environmental Protection Committee (MEPC)* by Canada in 1988 (IMO, 2009). As a response, the MEPC in 1991 adopted the first voluntary guidelines that were believed to prevent the introduction into the marine environment of unwanted aquatic organisms and pathogens from the claims on ship's ballast water and sediments discharges (IMO, 2009).

The *United Nations Conference on Environment and Development (UNCED),* which was held in Rio de Janeiro in 1992, raised the issue of the unwanted species in ship's ballast water as a major international concern was recognized. Guidelines were reviewed and were adopted as an assembly resolution 1993; however, it was superseded by a more comprehensive guideline in 1997 by resolution A.868 (20). The new resolution requested governments to take urgent action in applying these guidelines and report any experience gained in their implementation to the MEPC. The resolution also requested the MEPC to work towards the completion of legally binding provisions on ballast water management with the guidelines for their uniform and effective implementation (IMO, 2009).

In 1994, MEPC established the Ballast Water Working Group (BWWG), which focused on the preparation of a free standing Convention on control and management of ship's ballast water and sediments (IMO, 2009).

In 2002, the World Summit on the sustainable development held in Johannesburg, called for action alien species in ballast water and recognised the issues with introduction of harmful aquatic organisms and pathogens to new environments as one of the four greatest threats to the world's oceans (other three are land-sourced marine pollution, overexploitation of living marine resources and destruction of habitat) (IMO, 2009). The control and management of ship's ballast water is recognised as a major environmental challenge for IMO and the global shipping industry.

In 13th February 2004, the International Convention for the Control and Management of Ship's Ballast Water and Sediments (BWM Convention) was adopted in a diplomatic conference on ship's ballast water management was held at IMO headquarters in London (IMO, 2009). The MEPC at its 51st session in 2004 approved a programme for the development of guidelines and procedures for uniform implementation of BWM Convention. The programme was further expanded at the 53rd session of the MEPC in July 2005 to develop and adopt 14 sets of Guidelines as the last one was adopted in October 2008 (IMO, 2009).

The ultimate aims of this BWM Convention is to prevent, minimize and ultimately eliminate the transfer of harmful aquatic organisms and pathogens through the control and management of ship's ballast water and sediments to prevent risks to the environment, human health, property and resources arising from the transfer of harmful aquatic organisms and pathogens via ship's ballast waters (IMO, 2013).

The BWM Convention will enter into force twelve months after the date on which not less than thirty countries with a combined merchant fleets of the world's merchant shipping, constituting not less than 35% of gross tonnage of the worlds' merchant shipping, have either signed it without reservation as to rectification, acceptance or approval. However, this Convention has not entered into force yet, as of 6th January 2015, thirty six countries have ratified to the convention with 32.54% of the world's merchant shipping gross tonnage (for an update visit status of Conventions at **http://www.imo.org**). The convention will enter into force when the combined merchant fleets of which constitutes not less than 35% of the gross tonnage of the world merchant shipping have signed the Convention.

The International Convention for the Control and Management of Ships Ballast Water and Sediments is divided into 22 articles, 5 annexes and 14 guidelines which include technical standards and requirements regarding the regulations for the control and management of ship's ballast water and sediments.

The BWM Convention requires all ships including submersibles, floating craft, floating platforms, FPSO (Floating Production Storage and Offloading), to implement a ballast water and sediments management plan, to carry a ballast water record book and to manage their ballast water on every voyage by either exchanging or treating it using an approved Ballast Water Treatment System. It is worth noting that, the BWM Convention will not apply to the following:

- Ships not designed to carry ballast water,

- Warships, naval auxiliaries or other ships owned or operated by a state,
- Ships only on non-commercial service, or
- Ships with permanent ballast water in sealed tanks.

Regulation B-3 requirements for ship's ballast water management reported (IMO, 2009):

- Ships constructed **before 2009** with a ballast water capacity of between **1500 and 5000** *cubic metres* must conduct ballast water management that at least meets the ballast water exchange standards (D-1) or the ballast water performance standards (D-2) Until **2014**, after which it shall at least meet the ballast water performance standard.
- Ships constructed **before 2009** with a ballast water capacity of less than **1500 or greater than 5000** *cubic metres* must conduct ballast water management that at least meets the ballast water exchange standards or the ballast water performance standards **until 2016**, after which it shall at least meet the ballast water performance standard.
- Ships constructed **in or after 2009** with ballast water capacity of **less than 5000 cubic metres** must conduct ballast water management that at least meets the ballast water performance standard.
- Ships constructed **in or after 2009** but **before 2012**, with a ballast water capacity of **5000** *cubic metres or more* shall conduct ballast water management that at least meets the standards described in regulation D-1 or D-2 until **2016** and at least the ballast water performance standard after **2016**.
- Ships constructed **in or after 2012**, with a ballast water capacity of **5000** *cubic metres or more* shall conduct ballast water management that at least meets the ballast water performance standard (D-2).

It is very clear from regulation B-3 that the deadline for fitting of ballast water treatment facilities on new built ships under the coming Convention is for ships constructed in 2009 with ballast capacity of **less than** 5000 cubic meters. The enforcement of the first deadline was discussed and suggested to be postponed in MEPC 56/23 due to delays with ratification of the Convention and in the development of type-approved ballast water management systems.

D-1 and D-2 standards which were mentioned in regulation B3 are the two standards, which any ballast water management system should meet these requirements when applicable. The first standard is the Ballast Water Exchange (D1), which set out as interim measure to provide ship operator with guidelines of ballast water exchange in deep water, and the second standard is the ballast water performance (D2), which set a line for the biological quality of discharged ballast water, when a shipboard treatment system is installed.

The two standards are as follows (IMO, 2009):

1- D-1 Standard:

Ships performing Ballast Water exchange shall do so with an efficiency of 95 per cent volumetric exchange of Ballast Water. For ships exchanging ballast water by the pumping-through method, pumping through three times the volume of each ballast water tank shall be considered to meet the standard described. Pumping through less than three times the volume may be accepted, but at least 95 percent should be demonstrated by the ship. The operation of ballast water exchange by ships should be conducted according to the regulation (B4) of the Convention. In this regulation all ships performing ballast water exchange should:

- Whenever possible, conduct ballast water exchange at least 200 nautical miles from the nearest land and in water at least 200 metres in depth, taking into account guidelines developed by IMO;
- If the above is not possible, then ship should be as far from the nearest land as possible, and in all cases at least 50 nautical miles from the nearest land and in water at least 200 metres in depth.

2- D-2 Standard:

Ships conducting ballast water management shall discharge less than 10 viable organisms per cubic metre greater than or equal to 50 micrometres in minimum dimension and less than 10 viable organisms per millilitre less than 50 micrometres in minimum dimension and greater than or equal to 10 micrometres in minimum dimension; and discharge of the indicator microbes shall not exceed the specified concentrations.

The indicator microbes, as a human health standard, include, but are not limited to:

a) Toxicogenic Vibrio cholerae (O1 and O139) with less than 1 colony forming unit (cfu) per 100 millilitres or less than 1 cfu per 1 gram (wet weight) zooplankton samples;
b) Escherichia coli less than 250 cfu per 100 millilitres;
c) Intestinal Enterococci less than 100 cfu per 100 millilitres.

Once the BWM Convention has entered into force, all the ships of 400 gross tonnes (gt) and above will be required to have an on board BWM system, a ballast water record book, and should be surveyed and issued with an international BWM Certificate.
All BWTS need to be type approved by a Flag state before being sold to a client, it is worth noting that a BWTS that uses active substances has to undergo a more thorough certification process and obtain Basic and Final approval by the IMO. This process is initiated to proof the environmental acceptability of treated ballast water at the discharge (David et al., 2014). In addition, all BWTS are tested in a land base to show that D-2 standard is met by 10 cycles in minimum. Then, three test cycles need to be undertaken for at least 6 months on board ships to document that D-2 standard is met Figure 2-9.

BWMS	BWMS approval according to G9 (GESAMP and MEPC)	BWMS approval according to G8 (Flag state)	BWMS approval according to G9 (GESAMP and MEPC)	BWMS Type Approval Certificate (Flag state)
using active substance(s) →	Basic Approval →	Land based tests → Shipboard tests →	Final Approval →	Type Approval
without using active substance(s) →	→	Land based tests → Shipboard tests →	→	Type Approval

Figure 2-9: The approval process of BWTS according to IMO Guideline G8 requirements (David et al., 2014).

2.1.4.2 United States Coast Guard (USCG)

In addition to the IMO BWT Convention requirements, other notional bodies, in response to the national concerns, have established both regulations and guidelines to prevent the introduction and the spread of bio-invasion such as the United States Coast Guard (USCG). In response to the ecological and economic impacts of the zebra mussel invasion into the North American Great Lakes, the US Congress enacted the “Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990” (NANPCA) (ABS, 2013). NANPCA established the USCG’s regulatory jurisdiction over BWM. The enactment of the “National Invasive Species Act of 1996” (NISA) reauthorized and amended NANPCA and emphasized the significant role of ballast water in the spread of aquatic nuisance species (ABS, 2013). As a result, NISA mandated the continuation of the Great Lakes BWM program and charged the USCG with establishing a voluntary BWM program for all other USA ports (i.e. those outside of the Great Lakes) and required ships to submit BWM reports. In 23rd March 2012, the USCG issued its final regulations on BWM entitled "Standards for Living Organisms in Ship's Ballast Water Discharged in USA Waters," aimed at preventing the introduction and spread of aquatic nuisance species into USA waters through the ballast water of ships. In 21st June 2012, the final rule was issued and applies to all ships (USA flag, and non-USA flag), equipped with ballast tanks. All the ballast water management in the United States (US) is administered by both the United States Coast Guard (USCG) and the USA Environmental Protection Agency (EPA). US BWM regulations applies to all ships calling at USA or Canadian ports and planning to discharge ballast water must perform a ballast water exchange or treatment in addition to sediment management. USA navigable waters include the territorial sea as extended to12 nautical miles from the USA baseline.

USA BWM regulations specifically, exempted (crude oil tankers engaged in coastwise service and ships that operate exclusively within one Captain of the Port (COTP) zone). On the other hand, a ship equipped with ballast tanks operating in US waters must meet one of the following management methods (ABS, 2013):

- Install and operate a ballast water management system (BWMS) that has been approved by the USCG under 46 CFR 162.060;
- Use only water from a USA public water system;
- Perform complete ballast water exchange in an area 200 nautical miles from any shore prior to discharging ballast water, unless the ship is required to employ an approved BWMS per the implementation schedule Table 2-2;
- No ballast water is discharged;
- Discharge to a facility onshore or to another ship for the purpose of treatment.

The USCG added a provision to allow for a temporary acceptance of a foreign Administration's approval of a BWMS if it can be shown that the foreign-approved BWMS is at least as effective as ballast water exchange. This temporary acceptance, known as AMS, will be granted for five years from the date when the ship on which the installed BWMS is required to comply with the USCG regulations. However, it should be noted that, Once BWMS are type approved by the USCG and available for a given class, type of ship or specific ship, the additional ships in that group or category will no longer be able to install AMS in lieu of USCG type approved systems.

Table 2-2: USCG Approved BWMS Implementation Schedule

	Ballast water Capacity	Construction date	Compliance date
New Ships	All	On or after 1st December 2013	On Delivery
Existing Ships	Less than 1,500 m^3	Before 1st December 2013	1st scheduled Dry-docking after 1st January 2016
	1,500 – 5,000 m^3		1st scheduled Dry-docking after 1st January 2014
	Greater than 5,000 m^3		1st scheduled Dry-docking after 1st January 2016

The Coast Guard’s discharge standard is the same as the International Maritime Organization’s performance standard i.e. Regulation D-2 of the Ballast Water Management Convention. However, in 2009 the USCG also proposes a “phase-two” standard, which was more stringent than the IMO D-2 standard.

Some of the states have specific BWM requirements or standards. For example, California and New York are considered to have the most stringent requirements. Table 2-3 shows a comparison between the IMO standards and stringent California BWM requirements.

These differences on the numerical standards which are enforced by specific region or countries are one of the significant aspects that a ship-owner or/and operator is confronted with. In addition, these differences in regulations are also enforcing ballast water treatment system’s manufacturers and vendors to seek extra assessments and approval to their systems.

Table 2-3: Differences between the ballast water discharge standards between IMO and California; ml: milliliter, cfu: colony forming unit, µm: micrometre. (Source: adopted from (Commission, 2014))

Organism Size Class	IMO Standards	California standards
Organisms greater than 50µm in minimum dimension	< 10 viable organisms m^3	No detectable living organisms
Organisms10-50µm in minimum dimension	< 10 viable organisms ml	< 0.01 living organisms per ml
Living organisms less than 10µm in minimum dimension		< 10^3 bacteria per 100 ml < 10^4 viruses per 100 ml
Escherichia coli	< 250 cfu per 100 ml	< 126 cfu per 100 ml
Intestinal enterococci	< 100 cfu per 100 ml	< 33 cfu per 100 ml
Toxicogenic Vibrio (O1 & O139)	< 1 cfu per 100 ml or < 1 cfu per gram wet weight zooplankton samples	< 1 cfu per 100 ml < 1 cfu per gram wet weight zoological samples

Therefore, the author believes that it would be worth overcoming these differences in regulations in order to minimise risks of what is called not enough BWTS for all the ships today. Selection of the best BWTS would also be very challenging because some ships that don't normally change their trade routes can face the risk of no compliance with regulation if their trade routes ever changed. One can imagine the burdens of second hand ship's business which will be a challenge of the selection's problem for buyers that may require their ships to comply with more stringent regulation of a particular region.

2.1.5 Ballast water management (BWM)

Generally, ballast water management (BWM) can be categorised into five categories:

1. **Ballast Free Ship:**
    a. No ballast on-board (NBOB) ship
    b. Minimal Ballast Water (MBW) ship
2. **Port Reception:**
    a. Desalinating ship ballast water
3. **Ballast Water Exchange (BWE):**
    a. Sequential
    b. Flow through
    c. Dilution
4. **Filtration:**
    a. Screen filters
    b. Disk filters
    c. Hydro-cyclone
    d. Magnetic separation and coagulation
5. **Ballast Water Treatment System (BWTS):**
    a. Physical disinfection approach (e.g. Ultraviolet irradiation (UV), Ultrasound, Cavitation, De-oxygenation, Heat treatment, laser etc.),
    b. Chemical disinfection approach (e.g. Electrolysis, Ozonation, Sodium Hypochlorite, Chlorine Dioxide, High-energy plasma, Advanced Oxidation i.e. Titanium oxide (TiO_2) others) and
    c. Multi-components disinfection approach (e.g. Ozone + UV; Filtration + ozone + UV; filtration + Advanced Oxidation, others)

The explanations about some of the different BWM categories are discussed in the next section.

2.1.5.1 Ballast Free ship

The shipbuilding research centre of Japan (SRC) raised the concept of building ships with as little ballast water as possible in 2003-2005 (Technology, 2011). The national research led by the SRC investigated the concept of no ballast water ship (NOBS). The concept was created based on the early 2000s debates, held by IMO's Marine Environmental Protection Committee discussion on CO_2 emissions noting that 96% of green gas emissions from ships plans were drafted to reduce the amount ballast water (Technology, 2011). However, although this concept had potential of success, it had a significant drawback. This is because; NOBS would employ a slanted V-shape which would result in a ship with a far greater breadth and a narrower keel those conventional designs. This raised queries about the practicality of building and operating such ship with the amount of cargo that it would carry made such a concept viewed as an unprofitable venture, as a result the NOBS concept was put on hold until 2009. Thereafter the SRC had announced a new concept of the minimal ballast water ship (MIBS). MIBS concept was supported by the Japanese Ministry of Land, infrastructure, Transport and Tourism, focused on producing ships with that requires less ballast water and thus propulsion energy than existing ships. It was claimed that MIBS design will reduce the amount of ballast water by approximately 60-80 per cent while increasing propulsion efficiency. Japanese yards, supported by Japanese classification society Class NK, have been tasked, to develop the nominal MIBS tanker and bulk carrier design as one of the highest emitters of CO_2 (technology, 2011). The same concept was named "Variable Buoyancy Ship" presented at the Global R&D Forum on ballast water management systems hosted at the World Maritime University (WMU) as a fundamental paradigm shift (Parsons, 2010). The concept envisaged that ballast water tanks in conventional ship are replaced by ballast trunks beneath cargo space to allow these compartments to be flooded during ballast condition while the ship under way. It was envisaged that as to bulk carrier in motion, a continuous flow of local seawater moves through open these trunks (as a result of a natural pressure difference between the bow and the stern of the ship) and prevents ballast water to be carried to other location. When the bulk carrier is required to load cargo, the ballast trunks can be isolated from the ocean by valves, and then the water is pumped out using conventional ballast pumps. The ship was shown to use a closed trim system by using the fore peak tank and the AFT peak tank so that all traditional ballast is eliminated Figure 2-10.

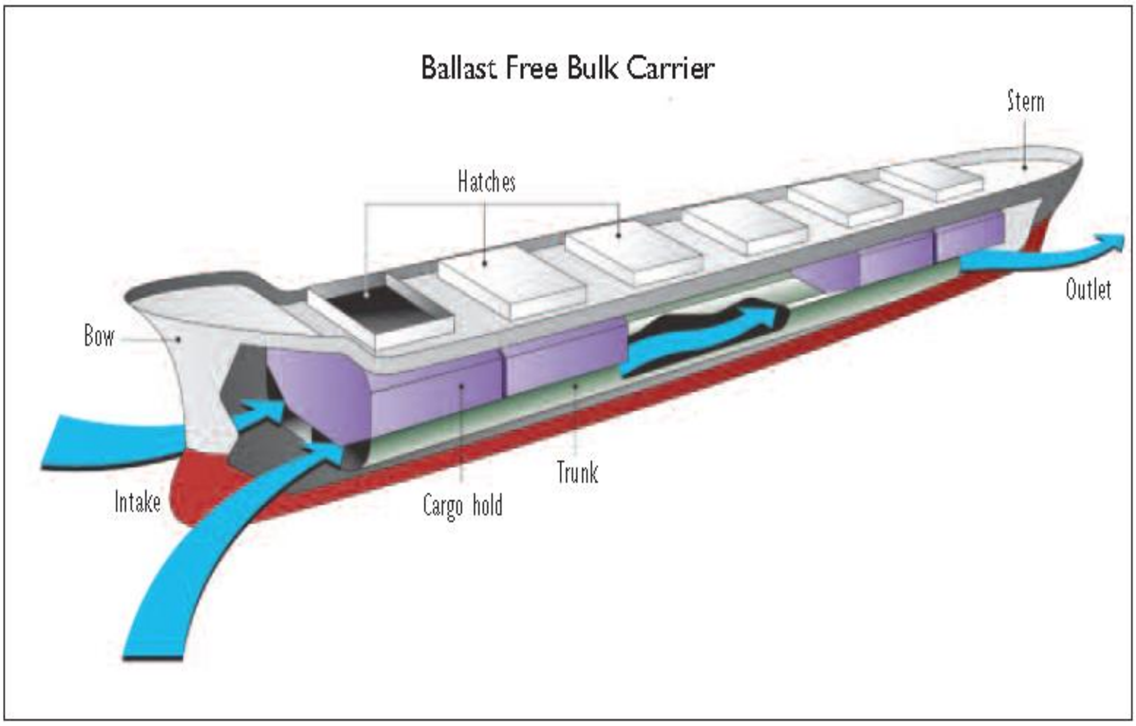


Figure 2-10: Variable Buoyancy of a bulk carrier (Parsons, 2010)

Through computer modelling and scale model tests both have shown that the concept is technically and economically feasible with ships operating at normal speed. However, the entire ship design needs to be redeveloped to support the proposed concept and it may only be suitable for certain types of ships. More validations and investigations would be required for the application for the detailed design before the full scale is required. It was also noted that this concept may not be suitable for all types of ships, because the entire ship design needs to be redeveloped to support proposed concept.

Other example of ballast free ship concept was investigated for a very large crude carrier (VLCC) that eliminates the requirement for ballast tanks by Det Norske Veritas (DNV) (Pazouki, 2012). It was claimed that the VLCC with this design would prevent the spread of invasive species. According to DNV, this design is called “Triality” due to three main objectives of creating an environmental friendly VLCC, using well known technology and being financially competitive.

2.1.5.2 Port reception

Port reception concept meant that the conventional ships remain unchanged however; the treated ballast is filled at ports like fuel bunkering. This method would not have microorganisms able to board ships which were supported in the literature (Donner, 2010).

Donner (2010) listed the advantages of port reception facilities over the on-board BWTS based on the following points:

1. Offers more economical approach. Assuming that ships would arrive in a regular base and thus treatment facility would be running continuously which is believed to be more effective than operating from time to time on ships.
2. Ship's crew are not water treatment experts. The shipping companies have to provide training for their crews to make them able to operate these treatments on-board. The fact that crew moves from ships to ship employer or within the company ships (different ships have different equipment) which may require more training for different types of treatments.
3. Additional requirements and obligation in some countries such as United States and other countries on ships. If ships does not pass the inspection, ships will be sent back to perform ballast water exchange (BWE) or pay fine which can be very costly. Inspectors may use such regulation as a demand for small bribe (or facilitation fee) to avoid having the ballast water to sampling or tests.
4. Port reception, would have permanent employees who could be better trained on running particular equipment. They can also be more focused on their work rather than ship's crew which have multi other tasks.

On the other hand, the concept of desalinating ship's ballast water is a new emerging concept as new paradigm shift to add value to the ships that suffers from fully ballasted return leg. Several studies investigated this concept such as (Sharma and Lande, 2010, Suban et al., 2010, Strategies, 2010, Sasaji, 1985), however, they have noted many drawbacks to this concept such as engineering issue, environmental issue, health issue, regulatory issue, economics issue and logistics issue perspectives. Therefore, the implementation of such a concept is still a challenge and requires more investigations.

2.1.5.3 Filtration

Filtration is a separation method which is generally used to physically remove organisms from water in many applications, such as the purification of drinking water, swimming pool water and in the recycling of grey water, as a primary treatment (Carney, 2011). In ships it was hoped to physically remove microorganisms during the uptake of ships ballast water. Several studies such as (Parsons and Harkins, 2002, Parsons, 2003, Riley et al., 2005, Tang et al., 2006, Xu et al., 2011) had different opinions about the bio-effectiveness based on the differences between test methods applied in each study (e.g. type of filter, flow rate, materials or organisms to be removed, source of water, location etc.). Generally it was found that neither of filtration treatments could meet IMO D-2 standard of the Ballast water Convention. Therefore, investigations have evolved toward the development of multi-components treatment approach (discussed later in this chapter).

The key objectives of filtration, according to (Parsons, 2003), can be listed as follows:

1. Protect the secondary treatment device from damage by larger heavy objects;
2. Improve the effectiveness of the secondary treatment by removing larger biota that are more difficult to kill allowing the secondary treatment to be optimized to affect biota that cannot be treated any other way;
3. Improve water turbidity if that will interfere with the secondary treatment process; and,
4. Remove non-biological material if that will interfere with (or consume) the secondary treatment.

There are many types of filter, three types of filtration have been tested for ballast water treatment (Parsons and Harkins, 2002, Parsons, 2003): screen, depth filtration and cyclonic. It is worth noting that these filters also vary in their approach for removing particles from the water. Screen filters are a commonly used type filter. They are composed of 'woven' or wires mesh screens and can be found as single or multi-layered. Larger particles than the pores are captured as the water flows through the screen filter, while smaller particles pass through. However, although the build-up of the larger particles on the screen filter enhances its effectiveness, it becomes a drawback as it will affect the speed of water flow through the screen due to clogging issue. Cleaning to restore the flow rate of the filter will be necessary by back flashing or replacing screens in order to maintain the performance. These drawbacks of screen filters, with clogging, increases the maintenance time required or/and the number of system back flash water time work and this was offset by the desk filters and crumb rubber depth filtration. These filters which can consist of sand, gravel, garnet and anthracite, that contain irregular pore sizes to trap particles do not have a standard pore size. When ballast water enters the filter system it must flow down the filter channels and as it passes through particles become trapped or adhere to the disc surface. These filters are generally designed with greater surface area available for particles to become attached it is often possible for the water to flow around trapped particles. This means that disc filters can function for longer periods of time than screen filters before they become clogged and the backwash process or cleaning is needed (Parsons and Harkins, 2002). Cyclonic separation is normally accomplished using hydro-cyclones. Depending on design and application, hydro-cyclones require less pump pressure than screen filters and allow separation of sediments and other suspended solids to approximately 20 μm.

The capital costs, system arrangement, net ballast flow were also investigated as factors for comparison between different filter types (i.e. screen, depth filtration and cyclonic) (Parsons, 2003). Parsons (2003) concluded that the disk filter is preferred (0.643) over the screen filter which was judged to be the second preferred technology, while and the hydro-cyclone was judged as the least effective option for meeting the overall goal of an effective primary treatment choice.

Another study such as (Riley et al., 2005) tested three different filtration train technologies (screen and disc followed by media filtration unit) at a pilot scale facility. Riley et al (2005) concluded that the media filtration system had a significantly superior performance to either the screen or disc filtration system. It is worth noting that the filtration method has been found as the most environmentally and socially- friendly when compared with Ultraviolet (UV) and a chemical treatment (Basurko and Mesbahi, 2012). It was highlighted, that filtration can be influenced by the train (arrangement of system or setup), type of filter used, size of the mesh, flow rate, maintenance, flash back pressure, adding chemical, however it was independent of temperature change, water quality etc. for example, Studies such (Tang et al., 2009, Tang et al., 2006) who suggested different material as a filter solution for ballast water treatment and investigated the application of crumb rubber filtration as a way to be utilised for ballast water treatment. This filter consists of a specific depth of crumb rubber and the filter efficiency depends on the size of crumb rubber particles used and the depth. In comparing between crumb rubber filtration with traditional granular filters, it was claimed that the crumb rubber filter used a much lower backwash water flow rate which reduces the size of the backwash pump and power requirement (Tang et al., 2006). However, the study also highlighted that the crumb rubber filtration did not meet the standards set by BWM Convention.

The size of the filter pores was investigated at removing taxonomic categories of zooplankton and phytoplankton using matched treatment and control ballast tanks (Cangelosi et al., 2007). Cangelosi et al (2007) found that the smallest pore sizes (i.e. 25 and 50 micrometre (μm)) performed better than the 100 μm at removing biological material. However, the study found no difference in the filtration efficiency of the 25 and 50 micrometre screens relative to macro- or microzooplankton. It was found that the 25 µm screen reduced both macrozooplankton and microzooplankton significantly more than the 50 µm screen. Zooplankton width was more determinative of filtration performance than length, and both filters removed loricate species of rotifers significantly more efficiently than aloricate species of the same length and width size classes. The 25 and 50 micrometre also significantly reduced algal densities, with the exception of colonial and filamentous green algae (50 µm only). Filter efficiency relative to algal particles was influenced by filter pore size, organism morphology and structure, and intake density, while algal particle size was not determinative. This research provides compelling evidence that 25 or 50 micrometre filtration is a potentially powerful means of reducing densities of organisms discharged by ships operating in the Great Lakes but an additional treatment step needed to effectively minimize risk and meet the IMO’s discharge standards.

2.1.5.4 Ballast water exchange (BWE)

The purpose of ballast water exchange (BWE) method is to replace coastal ballast water (and entrained organisms) with mid-ocean surface seawater. This is because it is believed that costal organisms will not likely to survive in mid oceans because of salinity differences, temperature, nutrition etc. There are three general methods that a ship can perform BWE which have been evaluated and accepted by the IMO (IMO, 2009):

- **Sequential method** – a process by which a ballast tank is first emptied and then refilled with replacement ballast water to achieve at least a 95 per cent volumetric exchange.
- **Flow-through method**– a process by which replacement ballast water is pumped into a ballast tank allowing water to flow through overflow on deck or other arrangements.
- **Dilution method** – a process by which replacement ballast water is filled through the top of the ballast tank with simultaneous discharge from the bottom at the same flow rate and maintaining a constant level in the tank throughout the ballast exchange operation.

According to the BWM Convention, if a ship decided to perform the BWE, whenever possible, it should be at least 200 nautical miles away from the nearest land and in water depths of at least 200 meter. If this is impossible, then BWE shall be conducted at least 50 nautical miles from the nearest land and in water at least 200 meter in depth. When this is also impossible, the BWE shall be conducted at least 50 nautical miles from the nearest land and in water at least 200 meter in depth. Where all these parameters cannot be met, then the port state may designate a BWE area, in consultation with adjacent other states, as appropriate (IMO, 2009).

Several issues have been reported with BWE method. This method poses safety risks due to the vulnerability of ships to excessive bending moments and stresses which may cause damage while the ballast tanks are emptied or over pressurised. In addition, this method cannot be carried out because it depends on the weather and location. For example, in intra-European shipping or domestic shipping of many countries (David and Gollasch, 2008). Moreover, several studies investigated efficiency of employing BWE on the existence of aquatic organisms, but varied in their results and conclusions (McCollin et al., 2007b, Gollasch et al., 2000, Leichsenring and Lawrence, 2011, Drake et al., 2002, Costello et al., 2007, Ellis and Macisaac, 2009, Gregg et al., 2009). The comparisons between all previous studies conclusions were also difficult as there were many differences between the studies such as the type of ships used, sampling difficulties, salinity differences, the geographic area of the voyages and the methods used to collect the samples, location from the nearest land, depth of the water, types and location tanks, seasons of each study, type of BWE method carried, species concerned and ballast tanks design. Based on all these differences some studies believed that BWE was an effective method (Ellis and Macisaac, 2009) who found 100 percent mortality employing BWE with gradual increase in salinity up to 30 percent over 72 hours; while other did not. For example, neither (Drake et al., 2002) nor (Leichsenring and Lawrence, 2011) studies found significant differences in Virus-Like Particle (VLP) abundance between exchanged and un-exchanged ballast water tanks. Other example, Costello et al. (2007), which used the time series of the first report of nonindigenous species in the Great Lakes to assess the effectiveness of voluntary policy of BWE in United States in 1990. They found that pre-policy invasion rate was constant, but was increasing with time, however, they also found that post-policy invasion time series is consistent with both policies (one had been somewhat effective and one had been counter-productive) (Costello et al., 2007). Their analysis demonstrated that, in contrast to other studies, discoveries on the effectiveness of BWE that has not been precise. Costello et al., (2007) believed that there was not enough information to estimate precisely the effectiveness of BWE policy. This was based on the time lag between introduction and detection of the nonindigenous species. Therefore, they reported that even if BWE was 100 percent effective, we should not be surprised by additional discoveries for the nonindigenous species (Costello et al., 2007).

Table 2-4 listed key, but not limited to, advantages and disadvantages for BWE. Acknowledging the studies above, the author believes that BWE can be reassessed in a more precise manner. This can be done by taking into account all the various differences between the previous studies in literature and then build a model to detect more accurately where it would be more effective. Although BWE got some drawbacks with regards to the possibility to carry out this method due to geographic location, safety of the ship, the dependence on weather, and not being effective in removing all organisms from ballast tanks; BWE actually, has got the advantage that might over weight these disadvantages like being the most applicable method to most ships, does not require additional costs for modification (new ship design) and treatment, document as an environmentally friendly method, does not require additional crew training. Therefore, the author believes it would be worth to overcome the limitations this method in a way to compromise between the bros and cons. Based on the literature, there is a significant potential that BWE is the best solution for one particular route or region and that would be an important point to shed light in future investigations.

Table 2-4: A short list summarising the advantages and disadvantages of BWE (Source: based on information from (Chase et al., 2001, Tsolaki and Diamadopoulos, 2009, David and Gollasch, 2008))

Advantages	Disadvantages
• Can be done while the ship is in route • Relatively little time is lost during the voyage. • No additional equipment or operator training is needed. • Low capital costs. • It is a simple process to implement. • Most ships can perform BWE. • No training is required. • Can effectively remove harmful organisms. • Environmentally friendly approach.	• Cannot completely remove all harmful organisms and sediments or residual matters from the bottom of ballast tanks. • Contend high risks to ship safety in bad weathers. • Cannot be performed everywhere as some countries do not have the IMO recommended depth and/or distance. • Proven its limited effectiveness in removing harmful organisms. • High operating cost, if continues BWE was performed. • High maintenance cost associated with operating pumps for long time.

2.1.5.5 Ballast water treatment Systems (BWTS)

As mentioned earlier, BWTS are being divided into three main types i.e. physical disinfection approach; chemical disinfection approach and multi-components disinfection approach. Examples on some of these types are discussed next.

2.1.5.5.1 Physical disinfection approach

2.1.5.5.1.1 Ultraviolet irradiation (UV)

Ultraviolet (UV) is a treatment methodology that bases its inactivation approach by damaging nucleic acids i.e. DNA and RNA. UV light is absorbed by bonds between base pairs in DNA and RNA molecules and causes the bond to become ‘open’ which stimulates the formation of covalent bonds, named “pyrimidine dimers” between bases and neighbouring bases. These bonds alter the structure of the DNA and RNA in a way to prevents DNA replications and results in organisms inactivation (Sassi et al., 2005, Kowalski, 2009, Wolfe, 2009). However, these pyrimidine dimers can be removed by two methods i.e. photo repair and dark repair which, causes failure to the inactivation. The UV light radiation can be divided into four different types Figure 2-11:

- Vacuum UV (100-200nm),
- UV-C (200-280nm),
- UV-B (280-315nm) and
- UV-A (320-400nm).

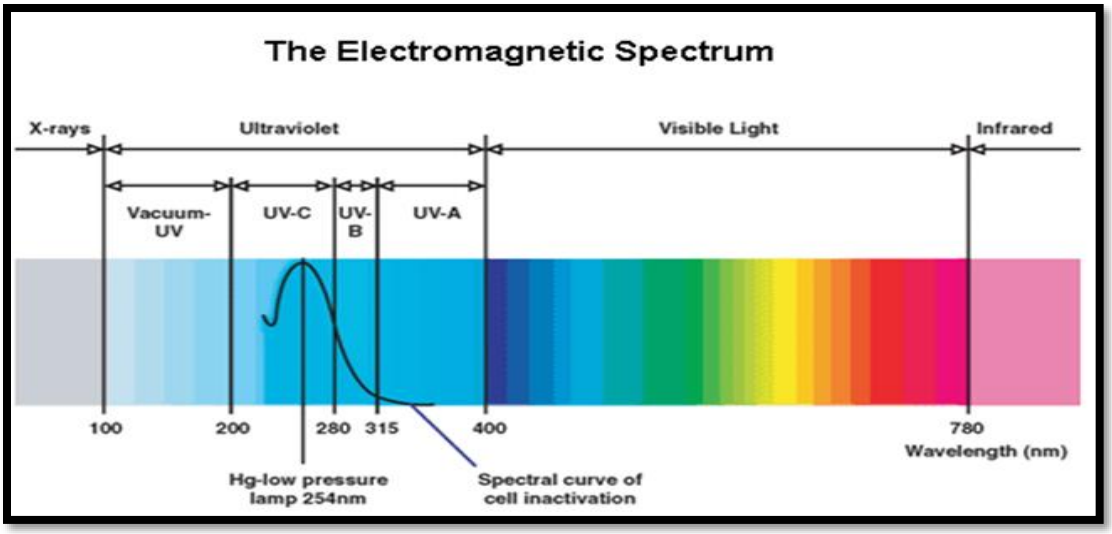


Figure 2-11: Electromagnetic spectrum and the ultraviolet (A,B &C) (coachingwork, 2010)

It is important to note that UV-A radiation (320–400 nm) is not considered germicidal, and Vacuum UV (100-200nm) is tend to be rapidly absorbed but can act as germicidal (Kowalski, 2009).While UV-B(280-320 nm) and UV-C (200-280 nm) are considered germicidal UV bands. UV light is naturally emitted by the Sun to the Earth. UV can be artificially produced by mercury vapour UV lamp. The light is created by applying voltage to a gaseous mixture resulting in emitting photons and depends on both the gas used and power level of lamp. Commercially there are two types of UV lamps (commonly mercury vapour): low (emits monochromatic light, 253 nm UV-C light) and medium pressure (emit polychromatic light, 210-230 nm UV-C light). Generally, a medium pressure lamp emits higher light intensity and as a result more energy output than low pressure lamps (Wolfe, 2009). UV lamps last approximately 8,000 -10,000 hours before changing is required (Wolfe, 2009).

UV disinfection has been widely applied for many years in drinking water (e.g. one of the world largest UV disinfection plant in London), sewage treatment, and swimming's pool treatment, pharmaceutical, cosmetic, hospitals, and beverages factories and lately used as one of the ship's ballast water treatment's methods. The UV disinfection approach has been reported as a feasible technology for ballast water application usually in combination with a preliminary treatment (e.g. cyclonic separation, ceramic filter etc.) (Sutherland et al., 2001, Xu et al., 2011, Sassi et al., 2005). These combinations were reported to improve the efficiency of the UV treatment by removing large particles and organisms (e.g. zooplankton and larger phytoplankton). However, organisms, bacteria and viruses required different UV doses and other seemed to be more resistant to UV inactivation such as protozoan cysts which requires higher UV doses (Wolfe, 2009). This was supported in (Gregg et al., 2009). Advantages of UV inactivation are: it does not contribute to by-products production (DBP), short contact times (seconds), temperature independent (Severin et al., 1983), low maintenance and operating cost ; however, risks associated with mutagenicity, determining effective doses (failure of inactivation), biofouling of lamps surfaces , lamp breakage, sensitivity to water clarity (e.g. turbid, colours, contains materials etc.) were also considered as issues of the UV treatments. In the literature, there are some inconsistencies in some conclusions about the UV effectiveness, e.g. sensitivity to temperature changes (Abu-ghararah, 1994), or not sensitive to changes (Severin et al., 1983). While acknowledging their perspective, the author believes that these studies may not be true when applied on-board ships for several reasons: the variety of organisms and particularly some organisms varied in their ability to survive different UV doses and different temperature exposure. On board ships there are many factors that may influence the inactivation abilities of UV treatment such as seawater clarity. Future studies about the influences factors of UV on-board ships with large organisms deserve more investigation.

2.1.5.5.1.2 De-oxygenation

De-oxygenation is a treatment methodology that bases its inactivation approach by removing the oxygen from the water. De-oxygenation has been considered as an environmentally friendly ballast water treatment. Based on the literature, de-oxygenation for ballast water treatment can be achieved by four ways:

1- Purging oxygen from ballast tanks by continuous supply of nitrogen (Tamburri et al., 2002).
2- Venturi Oxygen Stripping (VOS) (Tamburri et al., 2004).
3- Adding nutrients to stimulate the growth of bacteria (McCollin et al., 2007a).
4- Yeast based bioreactive de-oxygenation process (de Lafontaine and Despatie, 2014).

Tamburri et al., (2002) investigated whether if this approach is a cost effective, reduces corrosion; curb the introduction of organisms to limit bio invasions and to evaluate this treatment approach for its potential to treat ship's ballast water. Tamburri et al. (2002) observed a very quick drop in the oxygen percentage below 0.5% air saturation which remained extremely low for weeks to months. This observation with no detection of hydrogen sulphide (H_2S) was also confirmed in (McCollin et al., 2007a) as a result of reduced oxygen levels and thus it was reported that corrosion rate on test plates were lowered to about 10% than the oxygenated plates (e.g. 0.06 mm/year for nitrogen treated compared with 0.47 mm/year in oxygenated plates) (Tamburri et al., 2002). Therefore, Tamburri et al., (2002) argued that this treatment approach is a cost effective in the long run (25 years); particularly when considering the painting costs of a typical cargo ship of $10.9 million in compare with only $1 million when employing de-oxygenation treatment system to ballast water. Tamburri et al., (2002), suggested an alternative to Pressure Swing Absorption (PSA) a Liquefied Nitrogen Generator (LNG) that produces nitrogen by liquefying air which also have potential to lower the long run cost even further, in comparison to typical painting costs to ship's ballast tanks to prevent corrosion. Therefore, according to Tamburri et al (2002), de-oxygenation ballast treatment approach was believed to result in an economic benefit for controlling corrosion in addition to its potential at reducing the introductions of aquatic organisms.

De-oxygenation method revealed a significant mortality in larvae (e.g. *F. enigmaticus, C. maenas, and D.polymorpha*), as reported by Tamburri et al (2002), with estimates of 2-3 days and predicted a 100% larvae mortality during 2-3 weeks. In addition, it was reported in literature (Tamburri et al., 2002) that the majority of species would less likely to survive hypoxia more than 72 hours. Therefore, and based on the general ballast water treatment criteria i.e. safe for shipboard used, effective at killing potential invaders, environmentally friendly and affordable for ship-owners; (Tamburri et al., 2002) believed that the benefit of the anticorrosion criterion of the de-oxygenation with nitrogen can meet the criteria required by IMO. According the literature, the majority of organisms were found to less likely to survive hypoxic condition (Tamburri et al., 2002). This was supported by (Tamburri et al., 2004) with a notification to time to mortality which varied per organism per exposure to de-oxygenated ballast water.

The investigation about the de-oxygenation method was further investigated in (Tamburri et al., 2004) taking into account the biological efficacy on marine organisms, anti-corrosion ability, and costs for a more prolonged study of 1 year. Tamburri et al (2004) reported that de-oxygenation method of Venture Oxygen Stripping (VOS) i.e. removing oxygen from ballast water though introducing micro-fine bubbles of inert gas as water is being pumped into the tanks as one of the most efficient way for oxygen removal from ballast water. Maintaining de-oxygenated environment in ballast tanks appears to be critical factor for corrosion prevention and thus results in a significant decrease in ballast tanks maintenance cost (e.g. $5-10 per square meter, and approx. $500 square meter if corroded area) (Tamburri et al., 2004). Unlike the continues treatment in other BWTS approaches may enhance corrosion rates to ballast water tanks (Tamburri et al., 2004). Tamburri et al (2004) also observed greater than 99% mortality in zooplankton (e.g. copepods, barnacle larvae, polychaete larvae, cladocerans, crustacean nauplii, bivalve larvae and nematodes); however, it was found difficult to assess its impacts on phytoplankton. Nevertheless, the de-oxygenation ballast treatment approach appeared not to enhance bacterial growth or cause blooms (Tamburri et al., 2004).

McCollin et al (2007a) also investigated the de-oxygenation approach but in a different way by adding nutrients to stimulate the growth of bacteria in order to consume the oxygen within the ballast water tank to create hostile environment for aerobic aquatic organisms within the ballast tank. Although due to the difficulties of sampling access, mortality of organisms were lowered; however, it was noted that there was no significant effect in mortality of some organisms such as *copepods* and *nauplii*, indicating different sensitivity to this method. Other factors such as low pH, pump damage, and water temperature during voyage (e.g.18-30˚C) were noted as an important consideration to the biological efficacy (McCollin et al., 2007a). The D-2 standards were also claimed to be complied with after 5-7 days of treatment for the selected group of organisms (McCollin et al., 2007a). McCollin et al (2007a) also suggested that method would only be suitable for ships undertaking longer voyages. This is because it relies on gradual reduction of oxygen over time.

On the other hand, preliminary evaluation of the corrosion in ballast tank was carried in (Lee et al., 2006). Lee et al (2006) evaluated the corrosion of unprotected 1020 carbon steel (general ballast water tanks material) under oxygenated and hypoxic environment. Water chemistry, dissolved oxygen (DO), corrosion and corrosion products and weight loss after 101 days were investigated. Lee et al (2006) concluded that, after 101 days, the de-oxygenation method to seawater had changed the water chemistry i.e. lowered pH, showed higher sulphide concentration than oxygenated, microbiology and corrosion mechanism for the unprotected carbon steel. Corrosion was observed in both oxygenated and hypoxic environment, and notably the corrosion of the side coupons was generally higher than bottom ones. The rate of corrosion in the hypoxic was also shown to be generally lower i.e. 0.04 $ohms^{-1}$ corrosion rate for side coupons in hypoxic compared with 0.06 $ohms^{-1}$ for oxygenated (Lee et al., 2006). Interesting point noted by (Lee et al., 2006) that the bottom coupons, in oxygenated space, showed the lowest weight loss with an average value of 0.018g, whereas hypoxic coupons lost an average of 0.029g. Although both these averages of weight loss were both considered low, the hypoxic coupons were inconsistent with the corrosion rate measured in the same study. This study also noted that de-oxygenation can be easily lost with the introduction of oxygen. Therefore, it will lose its criteria with the opening of ballast tanks hatch, or when pumping ballast water in port with less likely to impose any threat to native organisms.

The performance of a yeast based bioreactive de-oxygenation for very cold water was assessed (de Lafontaine and Despatie, 2014). De Lafontaine and Despatie (2014) found that the temperature change has not affected the expected results of the treatment; however, length of the voyage duration was noted to be a significant factor.

2.1.5.5.1.3 Ultrasound

Ultrasonic technology is a novel technique which has been utilised in many applications such as water treatment, food industry (Sassi et al., 2005). Ultrasound treatment uses a high frequency energy spectrum ranging from 20 kHz to 10 MHz. The generated high frequency energy causes vibration in liquids to produce physical and chemical effects (Holm et al., 2008, Mesbahi, 2004) . A high frequency is generated by a transducer that converts mechanical or electrical energy into high frequency energy (sound) in the liquid. Ultrasound transducers are usually constructed of steel, titanium, aluminium, ceramic material, or in combinations such as aluminium stacked with ceramic discs. The generated high frequency waves tend to travel perpendicular to the resonated surface. When liquids are exposed to these high frequency vibrations, the physical and chemical changes result in cavitation, heat generation, pressure deflection and degassing to remove oxygen. Cavitation can be defined, according to (Holm et al., 2008), as the rapid formation and collapse of microscopic gas bubbles in liquid as the molecules in the liquid absorb ultrasonic energy. Cavitation is affected by the frequency of the ultrasonic wave, power level, volume of water, temperature and the concentration of dissolved matter and gases (Mesbahi, 2004). According to Mesbahi (2004), high frequency, warmer temperature and lower concentration of dissolved matter increases the effect of the unltrasound puleses including planton mortality. On the other hand, According to Mesbahi (2004), no risks to increased corrosion found with respect to coating and gaskets was found using ultasonic treatment. According to Sassi et al (2005), ultrasound technology does not seem to have any known environmental concerns.

Results obtained by Holm et al (2008) suggested that contact time and level of ultrasonic or energy is necessary to kill a range of organisms from bacteria to large zooplankton. Holm et al (2008) have also noted a relationship between the organism size, energy required and the contact time to achieve 90% mortality operating at 19-20 KHz.

2.1.5.5.1.4 Cavitation

Cavitation is achieved by many ways, like ultrasonic approach or hydrodynamic approach. Cavitation has been utilised in many applications such as enzyme recovery, microbial cell disruption, water and water waste disinfection and oxidation of pollutants. Cavitation for water disinfection usually coupled with conventional disinfection process like chlorination, ozonation or/and other chemicals.

2.1.5.5.1.5 Heat treatment

Heat treatment is based on the concept of rising the temperature of the water to a point where the targeted organisms cannot survive. A novel, cost-effective heating technique using waste heat from the ship's main engine was used to kill many unwanted organisms in ballast water (Rigby et al., 1999). In his experiment, the ballast water was continuously heated by the engine cooling before it is sent to ballast tanks reaching 38˚C. Rigby et al (1999) concluded that 38˚C is sufficient to treat ballast water with proper contact time in order to accomplish the heating operation. Also it has the potential to disinfect plankton and phytoplankton organisms with limited chance of survival.

The application of Rigby et al (1999) approach was denoted as short low temperature treatment (Quilez-Badia et al., 2008). Several issues were stated in Quilez-Badia et al (2008) on the short low temperature treatment as follows:

- Previous studies indicated that to successfully treat ballast water a temperature of at least 35˚C would have to be maintained for at least 20 hours. However, such a heat treatment approach may not be practical for many ships especially within Europe where they tend to operate in short voyages for ballasting operation.
- Discharging a large volume of hot ballast water into the receiving environment is not safe and may have other physical impacts on the ship for storing large volumes of heated water in ballast tanks.

Based on the issues above, Quilez-Badia et al (2008) examined the application of short term high temperature heat treatment on-board MS Don Quijote, a dedicated car-carrier. In their study the seawater was heated in two heat exchangers to 49-45˚C and the second heat exchanger increased it to the test temperature 55-80˚C using steam from the ship’s boiler. Immediately after the water reached the required treatment it was cooled prior to discharge to 22-27˚C. Quilez-Badia et al (2008) concluded that the results from their study show that short term heating to higher temperature can with some concerns achieve mortality for zooplankton that is comparable to heating water at lower temperature i.e. below 45˚C for longer periods.

However, the above proposed heat treatment approach had many issues i.e. cold weather condition can reduce the heat treatment effectiveness or requires additional modification to the piping or installation of large boilers, and in most cases it is difficult to achieve uniform heating rates (Boldor et al., 2008). Therefore, Boldor et al., (2008) studied the applicability of the microwaves heating. Microwave work by oscillating electric field components to excite the polar molecules in the liquid that vibrate or oscillate generating intermolecular and intermolecular friction coupled with movement of ions and results in instantaneous heating throughout the product (Boldor et al., 2008). Many advantages of using microwaves, According to Boldor et al., (2008), the microwave has a high heating rate due to its short heating and exposure span when compared to conventional heating, in addition it is also effective in non-clear water, less expensive to operate, and requires fewer accessories to install. The extent of heating produced microwave depends on the dielectric properties of the medium. Boldor et al., (2008), studied a continuous microwave heating system that was designed to process the ballast water and the effectiveness was tested against inactivation of various organisms. They concluded that the overall continuous microwave system could be used to deliver uniform heating loads that shows a promising an effective tool for ballast water treatment.

2.1.5.5.1.6 Pulse intense light treatment (PIL)

Pulse intense light (PIL) is considered as one of the most promising non-thermal sterilization technique in food industry (Feng et al., 2015). PIL technology uses short time pulses (100–400 μs) with an intense broad spectrum between 100 and 1100 nm to inactivate microorganisms (Feng et al., 2015). The peak power of each pulse is high; however, the total pulse energy is relatively low because of its short duration (Feng et al., 2015). Three key advantages of PIL in comparison with the traditional UV inactivation, according to Feng et al (2015): firstly, no toxic substances in xenon lamp in contrast to that of mercury in standard UV lamps; secondly, the UV irradiance of xenon lamp is about three or four orders of magnitude higher than that of UV lamp, which implies more effective and efficient inactivation ability; thirdly, microorganisms that expose to pulse intense light exhibit no tailing to their survival curves.

Feng et al (2015) first to test PIL to treat ship's ballast water under treatment condition of 350 pulse peak voltage on several types of microorganisms. Feng et al (2015) found that the increasing of the pulse peak voltage, the pulse frequency, and the pulse width have increased the inactivation of the selected microorganism significantly. However, Feng et al (2015) found that the energy consumption PIL treatment system is about 2.90–5.14 times higher than that of the typical commercial UV ballast water treatment system. Nevertheless, Feng et al

(2015) concluded that the results indicated that PIL is having potential for ballast water treatment with notable energy consumption challenge for such an approach.

2.1.5.5.2 Chemical disinfection approach

2.1.5.5.2.1 Ozone

Ozone treatment has been used for water disinfection purposes for more than a century. Ozone is an extremely strong disinfectant and was proved to be able to inactivate even more resistant pathogenic microorganisms such as *protozoa* in drinking water application (Von Gunten, 2003b, von Gunten, 2003a). Ozonation as a disinfection method has been used extensively for cooling water and municipal waste water in Europe and United States (Williams et al., 1978, Driedger et al., 2001). Ozonation is considered as an environmentally friendly treatment for ballast water, cost effective, and biologically effective with variability among organisms (Gregg et al., 2009). However, ozonation has some disadvantages with a major concerns of biocide discharge from ballast water, potential for imposing health and safety risks such as irritation to eyes and lungs (Gottschalk et al., 2009). Another issue with ozonation is the potential of increasing corrosion rate in ballast tanks (Sassi et al., 2005). Ozone is unstable in water and undergoes a number of reactions with some water matrix components. This leads to the formation of a potential human carcinogen by-product known as bromate (Driedger et al., 2001). Bromate works as a disinfection by-product (DBP) of the ozonation of bromide containing waters such as seawater. Figure 2-12 shows how the bromate is formed through a combination of reaction involving the ozone molecular the hydroxyl radical ($^{\bullet}OH$), and the bromide ion (Driedger et al., 2001).

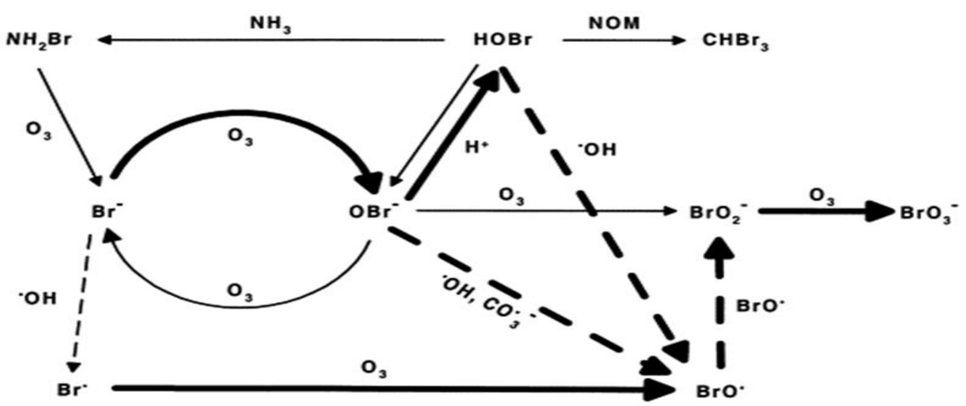


Figure 2-12: Reactions occurring upon ozonation of bromide containing solutions and bromate formation mechanism. Thick lines show the preferential mechanism during conventional ozonation processes (Driedger et al., 2001).

It is worth noting, that there is a big difference between ozone chemistry in seawater and freshwater (or sewage) is the presence of bromide ion (Br^-) in seawater, which influence the depletion of residual oxidants and therefore the persistence of the DBP varies as well as between the types of waters i.e. more persistent in seawater than in freshwater as presented Figure 2-13 (Liltved et al., 2006).

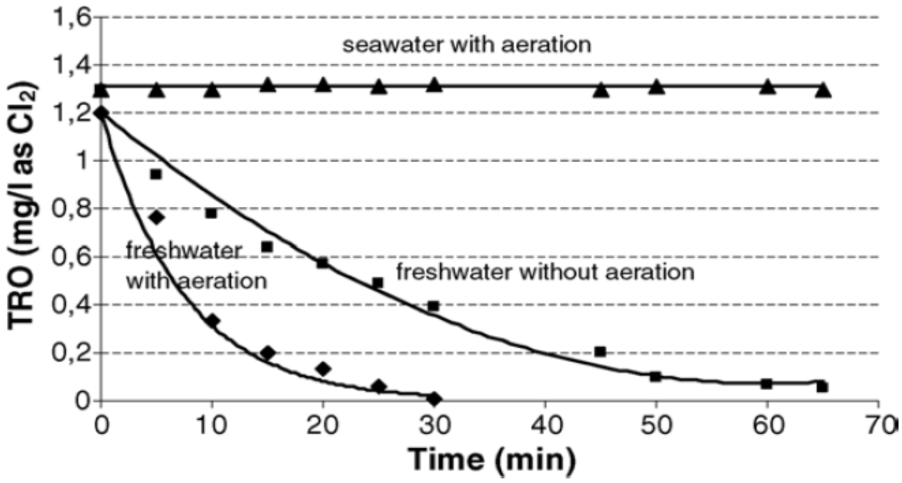


Fig. 2. Depletion of residual oxidants in ozonated fresh- and seawater at 9.5 °C. *Symbols:* (▲) seawater with aeration; (■) freshwater without aeration; (◆) freshwater with aeration.

Figure 2-13: The differences between the degradation rate (ozonated fresh and seawater water) of the residual oxidants over time (Liltved et al., 2006).

ozone is recommended for long contact time to obtain better disinfection results and less environmental risks (Oemcke and van Leeuwen, 2005b). However, materials contained in ballast water have been confirmed to influence the ozonation and its formed disinfectants. For example, Perrins et al (2006a) showed the sensitivity of ozone treatment to different waters chemical characteristics i.e. pH, salinity, nutrients such as phosphates, silicates, nitrates, nitrites, ammonia and total organic carbon (TOC). As a result, it was concluded that different ports water will require different doses of ozone to achieve the same initial by product formation and thus disinfection results (Perrins et al., 2006b, Perrins et al., 2006a).

On the other hand, Perrins et al (2006) also showed that the decay of the Total Residual Oxidant (TRO) was shown influenced by water salinity, organic matters, inorganic maters (iron), microorganisms, seasonal changes, temperature and light variation. These results may raise questions about the current ballast water treatment that utilize ozone for their ballast water treatment. However, other studies seem inconsistent with conclusions reported by Perrins et al (2006a &b) about the influencing effects (or toxicity) of ozonated seawater by the different chemistry (Jones et al., 2006).

Full scale ozone treatment testing carried out on an oil tanker *S/t Tonsina* (Herwig et al., 2006). They observed that ozone injected by bubbling ozone from diffusers into ballast tanks was unable to mix evenly throughout the tanks due to the number of internal structures and platforms within the ballast tanks that limited the water movement. This implied that bubbling method could be optimised in order to overcome the mixing problem or by designing ballast tanks in a way to allow such mixing or alternative injection method to be easier. TRO was observed to vary with the ozone injection method (Perrins et al., 2006b). Herwig et al (2006) also noted that the ozone treatment on selected organisms was found effective on *dinoflagellates* and *microflagellates* but less mortality was observed on shore crabs, *mysid shrimps.* While intermediate mortality on *Sheepshead minnows*, had the greatest mortality levels of them all. Interesting point is that the water chemical property i.e. salinity, water temperature, pH, dissolved organic compounds (e.g. phosphate, silicate, nitrate, nitrite, ammonium) varied between ballast tanks of the same ship. These differences may be considered as substantial points in assessing the TRO and decay rate as reported in many studies such as in Perrins et al (2006), and its consequences on the disinfection by utilising ozone for ballast water treatment. On the other hand, Herwig et al (2006) have also noted that the dissolved oxygen (DO) was relatively high at the beginning of the experiment (at ≥8 mg $l^{-1)}$ and did increase during ozonation with maximum levels of 2 to 3 times those of the initial levels (approx.. 20 mg l^{-1}) at the end of the experiment. This implied that ozonation could accelerate the corrosion of steel in ballast tanks where coating is deteriorated. This point was observed by the influence of ozone as strong depolarizer with the changes of temperature and pH to transfer the metal to the region of active dissolution, in which the corrosion rate increases considerably (Tatarchenko, 2004, Oemcke and Leeuwen, 2004).

A more recent ship full scale study on ozone treatment testing carried out on an oil tanker, *S/T Prince William Sound* (Wright et al., 2010). In *S/T Prince William Sound* tanker unlike in (Herwig et al., 2006), the ozone injection configuration was ejected differently via a venture system mounted in cargo pump room. Wright et al. (2010) also noted a high DO (approx.. 6.5 mg l^{-1}, and > 7.5 mg l^{-1} in trail 3) at the beginning of the test however lower than that reported in (Herwig et al., 2006). Wright et al. (2010) also observed that decay of TRO concentration of (1.2 ± 0.6 mg l^{-1} after 72hrs and 3.64±1.2 and 4.54± 0.84 mg l^{-1} of trails respectively for more than a week) which is relatively high and exceeds IMO guideline G9. Ozone was also noted as an effective treatment on selected organisms such as zooplankton, phytoplankton, *bacteria*, *mysid shrimp* and *topsmelt* and 100% mortality rate was observed.

However, the sensitivity to TROl^{-1} varied between the selected organisms (Wright et al., 2010). This point was also reported in an earlier study such as (Jones et al., 2006). Wright et al., (2010) observed 100% mortality of *topsmelt* although toxicity of water exposed by *topsmelt* was generally lower than that exposed to *mysid shrimp* with (median lethal concentrations (LC_{50}) geometric mean LC_{50} 0.51 to 0.83 mg TRO l^{-1} for an overall geometric mean LC_{50} of 0.67 mg TROl^{-1}). Herwig et al., (2006) also reported that dilution (12.5-50 %) to the treated water with clean seawater have influenced the toxicity to *topsmelt*. It was noted that different dilution percentage were required to eliminate toxicity in the different study trials (Wright et al., 2010). Samples were carried out on both laboratory and ship board base were noted in a good agreement between the two trials sampling location. Wright et al., (2010) concluded that the ozone treatment can meet the IMO BWM Convention regulation standard D-2 and the regulation standards of USCG phase 1. However, he showed less confidence in meeting the more rigorous phase of USCG (phase 2 standards). It is worth to note that different length of ozone experiments between different studies and the chemistry of water varied between such studies (Wright et al., 2010, Herwig et al., 2006, Jones et al., 2006). For example, one study went over 26hrs, or 5-10hrs, or less than 5 hrs.

Based on experiments carried on several marine invertebrate and fish species, ozone can effectively eliminate these organisms following a short-term (i.e., less than 5 h) ozonation at TRO concentrations of less than 1mg/L by products oxidants that can accumulate and remain toxic in closed containers for at least 2 days (Jones et al., 2006). They also showed that chemical treatments, such as $Na_2S_2O_3$, may provide a fast and effective means of reducing TRO concentrations without the risk of endangering organisms in the vicinity of the ship undergoing ozonation (Jones et al., 2006).

Other studies investigated the effectiveness of enhanced oxidation degradation of pollutants by generating the highly reactive hydroxyl radical ($^{\bullet}OH$) such as ozone in combination with titanium dioxide photo-catalysis (UV/Ag-TO_2 +O_3) (Wu et al., 2011a, Wu et al., 2011b). Wu et al. (a,b 2011) observed an enhanced inactivation of E.coli by utilising the UV/Ag-TO_2 +O_3 in comparison with results of utilising single treatment such as ozone or UV by itself. Results also indicated that the presence of UV/Ag-TiO_2/O_3 process can expedite the inactivation of *E.coli and Amphidinium sp*. Both ozone doses were observed to influence the inactivation efficiency as for the UV doses. These results were consistent with the results from the study in Oemcke and van leeuwen (2005). The decay of the TRO was also observed to decrease with time consistent with the study in Perrins et al (2006). Wu et al. (2011) concluded that

(UV/Ag-TO2 +O3) is an effective process to inactivate *E.coli* and have potential as a ballast water treatment.

2.2 Marine Vehicles

2.2.1 Marine Vehicle Background

Marine vehicle types can be divided into seagoing and inland water types. The seagoing marine vehicles can also be divided again into transporters (e.g. passenger, general cargo and bulk cargo) and non-transporters (e.g. fishing, military etc.). Transporters marine vehicles can be divided again into a number of broad categories Figure 2-14. Note that the red arrow represents the combined-purpose type of ship. It is worth noting that ballast water management is required to be implemented by all these ships based on each ship ballast water capacity and year of build. However, non-transporters (e.g. military ship) are excluded from the BWM convention just like other regulations (e.g. banding the use of tributyltin (TBT) antifouling compound).

Before going deeper into shipping it is worth noting a comment by one of the most thorough investigation reports "Rochdale Report" which was quoted there in the book of Maritime Economics (Stopford, 2009b) by Dr. Martin Stopford who's also a well-recognised expert in maritime shipping and the shipping industry: *"Shipping is a complex industry and the conditions which govern its operations in one sector do not necessarily apply to another; it might even, for some purposes, be better regarded as a group of related industries. Its main assets, the ship themselves, vary widely in size and type; they provide the whole range of services for a variety of goods, whether over shorter or longer distances. Although one can, for analytical purposes, usefully isolate sectors of the industry providing particular types of service, there is usually some interchange at the margin which cannot be ignored (Waltham 1972)".*

Marine vehicle can be divided into three main categories:

1. Tramp (irregular)
2. Liner (regular)
3. Passenger shipping

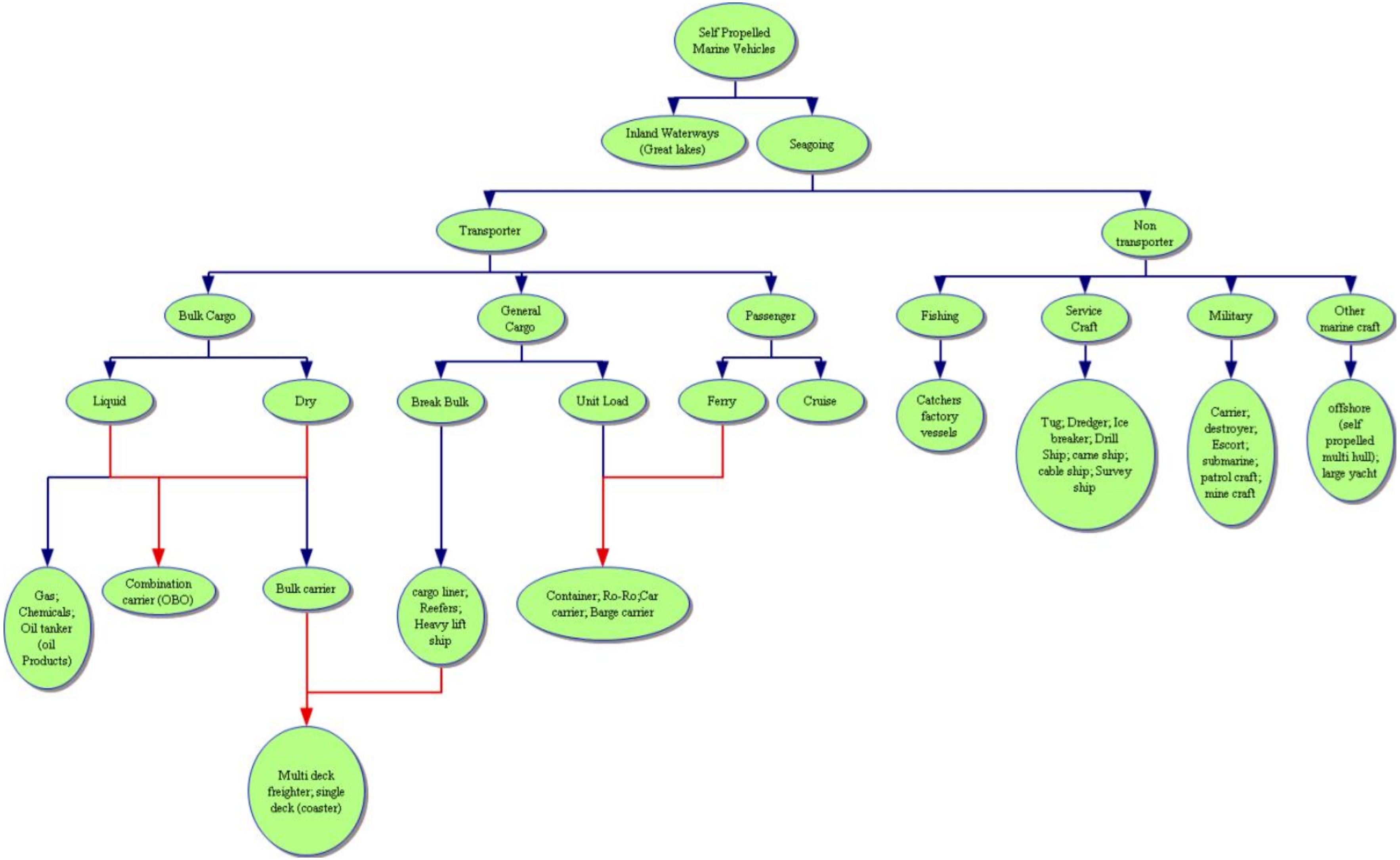


Figure 2-14: Division of the world marine vehicles, the red arrows represents a combined-purpose type of ship

Figure 2-14 shows that marine vehicles division fall into two main types according to its purpose built, and then it is divided again according to the cargo carried, which is again distinguished as two main divisions. These two main types are the ‘Liner' trade and the ‘Tramp' or 'Bulk' trade (ICS, 2005b).The tramp shipping is then divided as dry cargo and liquid cargo i.e. its ships are known as ‘Tankers’ or 'specialised tramps'. Dry bulk cargo are cargo that maybe be either loose, grained, free flowing, or solid, however, is not shipped in packaged form and it is often handled by special mechanical handling equipment that are specially designed for dry bulk terminals. Major dry bulk cargos are iron ore, grain, coal, bauxite, sugar, fertilizers, salt, sand, gravel and scrap metal. Liquid bulk or tanker cargo is a special constructed or converted ship to carry such liquid cargo. Major liquid cargos are crude oil, products oil, and chemical tankers, liquefied natural gas (LNG), liquefied petroleum gas (LPG), wine, molasses, vegetable oil. Liner cargo are classified as two types: i.e. container ships and general cargo ship; container ships carry their entire load in truck-size containers, whereas general cargo ships, which include, for example, RORO (roll-on/roll-off) ships and cargo liners, which may carry cargo as loose goods.

It is worth noting here that there are many differences between these types of shipping categories. Thus, one should consider all these differences when dealing with different types of ships when selecting a ballast water treatment system (BWTS). Some of the differences are discussed next.

2.2.1.1 Operation mode

One important difference between the two main shipping divisions i.e. Tramp and Liner shipping is the way how each division operates. For example, liner shipping is a term used to describe a cargo ship that operates between scheduled advertised ports on a regular basis, and of which most of the cargo is containerised (Monroe and Stewart, 2005). On the other hand, tramp shipping does not follow an advertised schedule like ‘liner-trade’ shipping, but it goes where the market draws it. Therefore it is called 'tramp' also because it tramps from place to place in search of cargo (ICS, 2005b). Thus in a tramp trade shipping, the ship may load cargo at Port ‘A’ and discharge it at Port ‘B’, and, if there is no cargo to load at Port ‘B’, it will sail empty, fully or partially ballasted with sea water, to Port ‘C’, load there, then proceed to Port ‘D’. Such an operating mode is an important criterion when considering the selection of a BWTS.

2.2.1.2 Changing trade route

Another important difference between the two main shipping divisions i.e. Tramp and Liner shipping is in the change of the trade route. For example, it is very hard, but not impossible, for a liner shipping to change its trade route. This is because liner shipping such as container ship run likes a bus service, no matter even if they were carrying empty containers. Captains in a liner ship have to stick to their scheduled routes and their advertised ports of call according to the time and date of delivery. On the other hand, tramp is likely to change its trade route direction depending on the market and cargo availability. Therefore, the process time for treating a ballast water capacity between the two types of shipping is an important parameter when considering the selection of a BWTS.

2.2.1.3 Ship management

Shipping is ultimately controlled by a group of people (shippers, charters, ship-owners, brokers, shipbuilder, bankers and regulators) who work together on a constantly changing task of transporting cargo (Stopford, 2009a). In shipping business the primary risk takers are the ship-owners i.e. the legal owners of the ship and/or the charters i.e. the people who hire ships from ship-owners under different types of contract and in some cases can be considered as the ship-owner (Stopford, 2009b).
In shipping, there are many risks associated with the fluctuating of fright rate and market cycles (Stopford, 2009a). Therefore, ship-owners tend to vary in the way of how they manage their ships in order to survive such fluctuation in markets, by minimising risks of unnecessary costs based on their confidence about the future. For example, one of the significant risks that a ship-owner faces is the ship costs which can be classified into five categories (Stopford, 2009b):

1. **Operating cost**: which constitute the day to day expenses of running the ship such as (crew wages, bunkering, stores, maintenance etc.);
2. **Periodic maintenance**: which are costs occur when the ship is dry docked for repairs which usually at the time of its special survey (in older ships this could be very significant expenditure and not treated as part of operating expenses);
3. **Voyage cost**: which are variable associated with a specific voyage and includes ports charges, fuel and canal dues, speed, towage etc;
4. **Capital cost**: Depends on the way how the ship has been financed;

5. **Cargo handling costs**: represents the expense of loading, stowing and discharging cargo (very important in liner shipping).

Based on the above costs, ship-owners are found to manage their shipping in many different ways in order to survive the fluctuating markets and the costs risks. For example, a ship owner may choose to manage his shipping stock in many different ways (ICS, 2005a):

- **Altering storage numbers**. This is done by converting the ship to an alternative use, such as a floating storage facility. For example, large oil tankers were and still are adapted to be used as floating oil stores; and large bulk carriers can be used to act as grain-storing silos.
- **Altering layup**. This is done by altering the active ship stock 'laying some ships up'. Here, the company (ship-owner) avoids the additional costs of preparing for layup a ship that has spent a long time in anchorage by leaving that ship with a company that provides management and maintenance services for it. This method is implemented when it is more cost-effective than making a ship fully operational again, only to face the prospect of incurring a loss if the ship trades at a very low rate for any sustained period of time. When demand condition improves sufficiently to warrant the operation of the full ship stock, laid up ships can be brought back into commission fairly rapidly.
- **Altering ship speeds**. Ship speed can be altered, and journey time can be reduced. This means that the same ship stock can achieve a larger volume of cargo throughput in any given period of time. However, there are limits on the use of this method, as the range of speeds depends upon engine design and efficiency. Ships are often designed and optimised for a particular range of speeds.
- **Altering the proportion of time at sea to time in port**. The point of this method is to reduce turnaround times in ports, and therefore sail more frequently in a given period. That produces more output in a given time. However, if port time is lengthened for any reason, or port congestion occurs, shipping supply will be reduced.
- **Altering the balance of laden voyages**. Alteration of cargo throughput is achieved by altering the proportion of laden to ballast voyages. Seaborne trade is 'unbalanced' when that the cargo volume delivered in one direction is larger than that delivered in the opposite direction. Tramp shipping, especially in the tanker trade where most journeys are laden only in one direction, is an extreme example of this. In this case, 50% of the potential cargo carrying space is wasted.

There are other ways that ship-owners, may choose to survive the market's risks such as distributing the amount of risks (e.g. apportionment costs) between the ship-owner and the charterer. For example, the costs and risks which discussed earlier in this section are distributed differently by three charter types i.e. voyage charter, time charter and bare boat charter Figure 2-15.

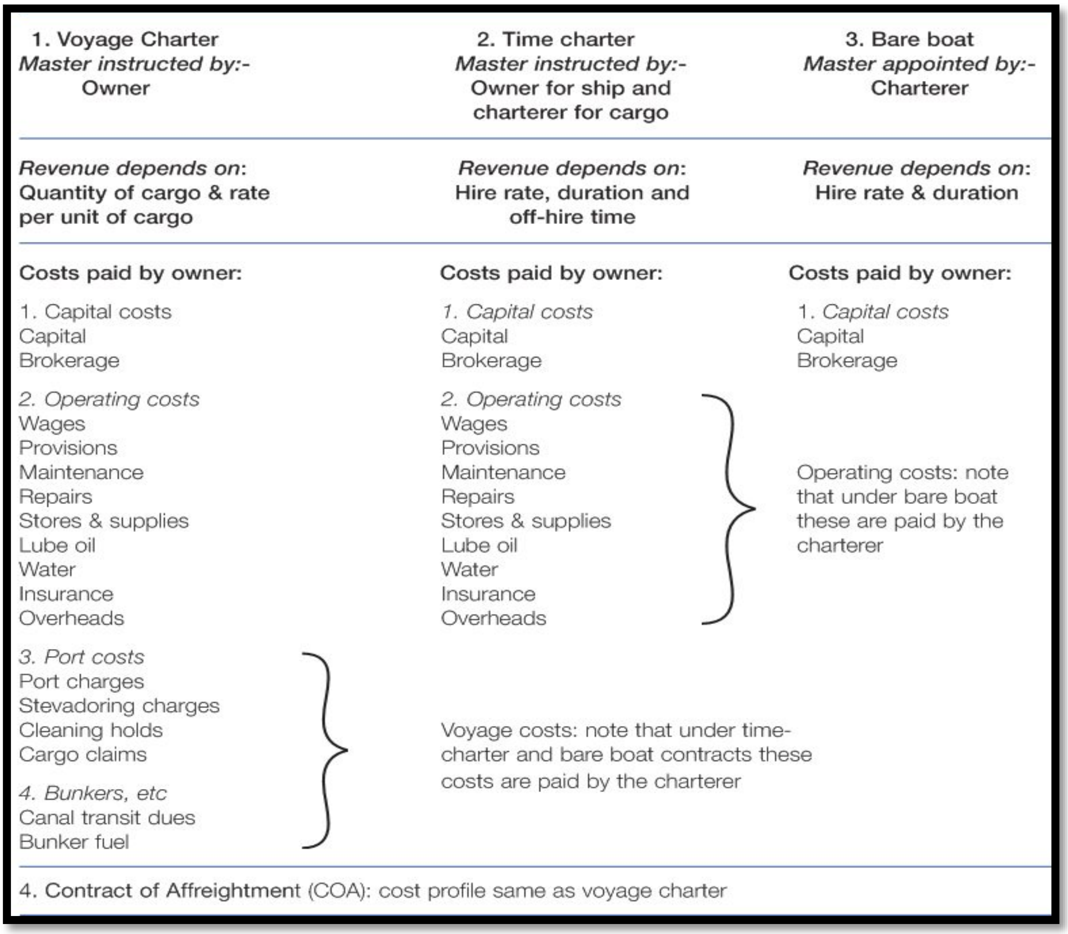


Figure 2-15: Voyage, time and bare boat charter types and cost distribution (Stopford, 2009a)

The voyage charter provides transport for a specific cargo from A to B for a fixed price per ton. It is worth noting that the ship-owner may charge extra fees named as 'demurrage' if the voyage is not completed within the terms of charter-party and conversely if the charter spends less time in port, for example, he can claim despatch to the owner (these are stated in dollars per day). On the other hand the Contract of Affreightment (COA), where a ship-owner agrees to carry out a series of cargo for a fixed price per ton. Here the charter is able to arrange the shipment at an agreed price per ton and leave each voyage details to ship-owner (switch cargo between his ships, arrange backhaul cargoes etc.). The time charter provides the charter with the operational control of the ships carrying his cargo, while leaving ownership and management of the ship in the hand of the ship-owner. The length of the charter may be the time taken to complete a single voyage (trip charter) or a period of time in months or year (period charter). The bare boat charter, provide the ship-owner to minimise all the risks and cost while still own the ship. This provides the charterer to have full operational control of the ship and pay all the operating and voyage costs. Therefore, in shipping business, ship-owners management strategy and objectives may vary thus it will have the potential to influence their criteria in the selection of the most feasible BWTS. For example, in a quick meeting, the author discussed the problem of the incoming BWM convention with two different ship owners and raised the issue of the BWTS selection with two different ship-owners at different location and time. One ship-owner responded: "*Cost is the most important thing to me*". The second ship-owner, in contrary to the above statement responded: "*It does not matter what type of ballast water treatment system or the costs associated with it, what matters to me is the compliance of my ships to the international regulation*". Based on the latter statements, although it is not plausible to base our decision on two quick questions/answers; however, the two different points of views have clearly indicated that there is potential of differences in the judgments for criteria between ship-owners when selecting a BWTS. The last point initiated the need to investigate this issue in this study.

2.2.1.4 Ship size

Today there is a significant difference between ships sizes. This is in order to meet their ultimate purpose depending on their voyage length and the type of cargo they carry Figure 2-16.

Crude oil tankers	
ULCC, double-hull	350,000 dwt plus
ULCC, single hull	320,000 dwt plus
VLCC, double-hull	200,000–349,999 dwt
VLCC, single hull	200,000–319,999 dwt
Suezmax crude tanker	125,000–199,999 dwt
Aframax crude tanker	80,000– 124,999 dwt; moulded breadth > 32.31m
Panamax crude tanker	50,000– 79,999 dwt; moulded breadth < 32.31m
Dry bulk and ore carriers	
Large capesize bulk carrier	150,000 dwt plus
Small capesize bulk carrier	80,000–149,999 dwt; moulded breadth > 32.31 m
Panamax bulk carrier	55,000–84,999 dwt; moulded breadth < 32.31 m
Handymax bulk carrier	35,000–54,999 dwt
Handysize bulk carrier	10,000–34,999 dwt
Ore/oil Carrier	
VLOO	200,000 dwt
Container ships	
Post-Panamax container ship	moulded breadth > 32.31 m
Panamax container ship	moulded breadth < 32.31 m

Figure 2-16: An approximate ships group's size in deadweight (dwt) (UNCTAD, 2010)

Figure 2-16 shows a contemporary approximate of different ships sizes and groups, according to the *United Nations Review of Maritime Transport (2010)* and what is generally used by shipping terminology today. Therefore, ship size in deadweight can be considered as an influencing parameter when selecting a BWTS.

2.2.1.5 Ship Age

The continues progress in ship technology combined with the cost of aging over twenty or thirty years life of a ship has a significant economic problem (Stopford, 2009b). As ship ages its capital cost reduces. However, it's operating & maintenance and voyage costs increases in compare to the newer ships. This argument is confirmed in a comparison study, in (Stopford, 2009b), between the annual costs of three Capesize bulk carriers compared the annual cost of three Capsize bulk carriers a 5, 10 and 20 years old respectively Figure 2-17. All three ships were trading under the Liberian flag, using the same crewing arrangement and charging capital 8% per annum. The overall cost per day works out at about the same for 5 and 10 years old ships but not the 20 years old which was about 13% more expensive to run. However, considering direct cash cost only and excluding capital cost and periodic maintenance, modern ships were shown to be cheaper to run. The difference is due to that as ship's ages, operating costs increases and more routine maintenance become necessary.

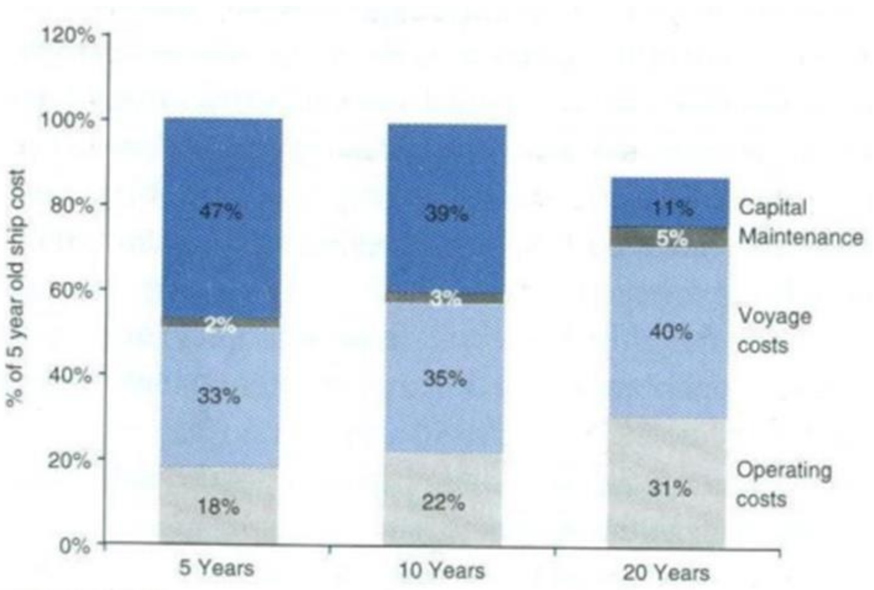


Figure 2-17: Relationship between cost and age for a capsize bulk carrier (Stopford, 2009b)

Since a BWTS will be added to the ship's machinery, it will contribute to the daily operating cost and capital cost (e.g. fuel consumption costs). Therefore, the ship's age can be defined as an important parameter for the selection of the most feasible BWTS.

2.2.1.6 Length of voyage

Liners have fixed trade routes while tramp don't follow specific trade patterns unless the market drive them to it. Therefore, in liner shipping the length between the voyages are very easy to predict precisely and thus one may plan for the optimum speed and length of voyage in order to arrive by the specified time and date. However, depending on the contract or charter type, it is difficult to predict the voyage length in tramp shipping. This is because a ship may or may not require sailing empty to secure a cargo in a closed by location. Therefore the length of voyage can be an important parameter when selecting a BWTS.

2.3 Critical review on the selection of the best BWTS

The challenge of comparing and selecting the best BWTS has becomes the task of contemporary researchers. There are many studies have investigated the problem associated with the comparing and the selection of a ballast water treatment system which we wish to selectively and critically review to identify the major gaps in the literature next in this section.

It is worth noting that, BWM Convention (2009) under regulation D-3.3 stated*:" Ballast Water Management systems used to comply with this Convention must be safe in terms of ship, its equipment and crew*". In addition, Regulation D-5 of the BWM Convention also listed the criteria for determining the appropriate BWTS that can meet regulation D-2 as follows:

1. Safety consideration relating to the ship and the crew.
2. Environmental acceptability, i.e. not causing more or greater environmental impacts than they solve;
3. Practicability, i.e. compatibility with the ship design and operations;
4. Cost effectiveness, i.e. economic; and
5. Biological effectiveness in terms of removing, or otherwise rendering not viable, Harmful Aquatic Organisms and Pathogens in Ballast Water.

The comparison between different treatment systems is difficult (Perakis and Yang, 2003). This is because Perakis and Yang (2003) believed that it is almost impossible to determine the overall cost and benefits of each BWTS. Perakis and Yang (2003) carried out a comparison between the different BWTS based on the operating and the capital costs of them. Perakis and Yang, (2003) raised the economic issues associated with the required freight rate (RFR) for installing a BWTS such as filtration, and suggested that it is cheaper to install BWTS for new built ship than the cost of retrofitting's an existing ship considering the costs of installation, filters, enlarged ballast pumps, piping and valves, electronic equipment, cables, breakers etc (Perakis and Yang, 2003). Perakis and Yang (2003) argued that since the average earning freight rate for 20 years ship estimated as \$0.02 per ton (for zero interest loan and saving from tank cleanings), ballast water exchange (BWE) seems more feasible than filtration (at estimated payback of \$0.099 per ton). Perakis and Yang, (2003) also warned if the additional costs were to be imposed in shipping for treating their ballast water to exceed their RFR, a modal shift from marine to other modes of transports (e.g. trains, plans, roads) may become a serious issue. Perakis and Yang, (2003) claimed that this issue with the modal shift is not affecting the shipping industry only but also may lead to more concerns related to the environmental pollution, safety, fuel efficiency, noise, transport safety etc.

In 2004, another paper found in the literature emphasised factors to be considered when choosing the best BWTS. Their views did not vary from the one identified by BWM Convention (Rigby, 2004). Rigby (2004) suggested that when choosing the best BWTS factors such as the following should be considered:

1. Legality or Adherence to Regulations i.e. must comply with all parties standard including the most stringent requirement by particular party.
2. Safety (e.g. safety of the ship and its crew at all times).
3. Biological Treatment Efficiency i.e. performance by eliminating harmful organisms.
4. Environmental Acceptability i.e. must not present any environmental risks or by products etc.
5. Practicality.
6. Costs.
7. Certification and Approvals.

The possible future challenge with the biological efficiency of a BWTS from one ship voyage to another has also been highlighted (Rigby, 2004). Rigby, (2004) argued that the interaction of factors such as seasonality and voyage parameter as an influence parameter need to be taken into account in identifying the best BWTS alternative. In addition, Rigby, (2004) explained that the practicality aspects, and highlighted several points when choosing the most appropriate BWTS options such as follow (Rigby, 2004):

- Analysing and complying with the required standards;
- Space required for the treatment;
- Process requirements (e.g. chemicals, valves, storage, delivery etc.);
- Performance monitoring;
- Maintenance;
- Time required for treatment process;
- Capacity limitations;
- Ease of operation;
- Possible effects on ship's operation;
- Risks to personnel and/or ship's safety; and
- Approval/demonstration processes.

For the cost, as a factor which involves both the installation and the operation of ballast water treatment system, Rigby (2004) believed that it will have a significant influence on the selection of a specific BWTS option but should be less weighted at this stage. This is because, Rigby (2004) believed that the development of new technologies and equipment, the cost data will not be available and if they were, then there will be limited small scale experiments of investigations. In addition cost of the installation of a BWTS can vary considerably from one type of ship to another. For certification and approvals factor, (Rigby, 2004), raised some concerns regarding the process of surveying and certification which already have been reported by IMO ballast water convention under article 7, and the issue of the selection when these test regimes become too prescriptive. Therefore, concluded that choosing the 'best' option requires an evaluation of a range of factors in which each will have a bearing on the final selection (Rigby, 2004).

In 2003, a study compared between three primary ballast water treatment devices namely: screen, disk and hydrocyclone filters which have been carried out (Parsons, 2003). The study objective was to report on the investigation of various ballast water system issues which must be considered in the selection and design of the primary ballast water treatment system. According to a study which considered the particle count efficiency (Parsons and Harkins, 2002). Parsons and Harkins (2002) demonstrated that both screen and disk filters with 50 and 100 micron respectively resulted above 90% efficiency while the hydrocyclone mean count efficiency with 100 micron was the lowest (above 30%). Parsons (2003) reported that the selection of the best primary treatment for ballast water is a discrete multi-criterion optimisation or decision making type of problem. Therefore, Parsons (2003) applied the Analytical Hierarchy Process (AHP) method which permits the ranking of discrete decision options and arranged the factors in hierarchy of relationships for the selection of a primary treatment device for a ballast system Figure 2-18. Figure 2-18 shows a balance of criteria such as particle removal efficiency; net ballast flow, arrangement impacts, maintainability and capital costs were considered for selecting the optimum primary treatment. The safety of the ship and crew were not identified in the hierarchy; however claimed to be considered as paramount in his decision model.

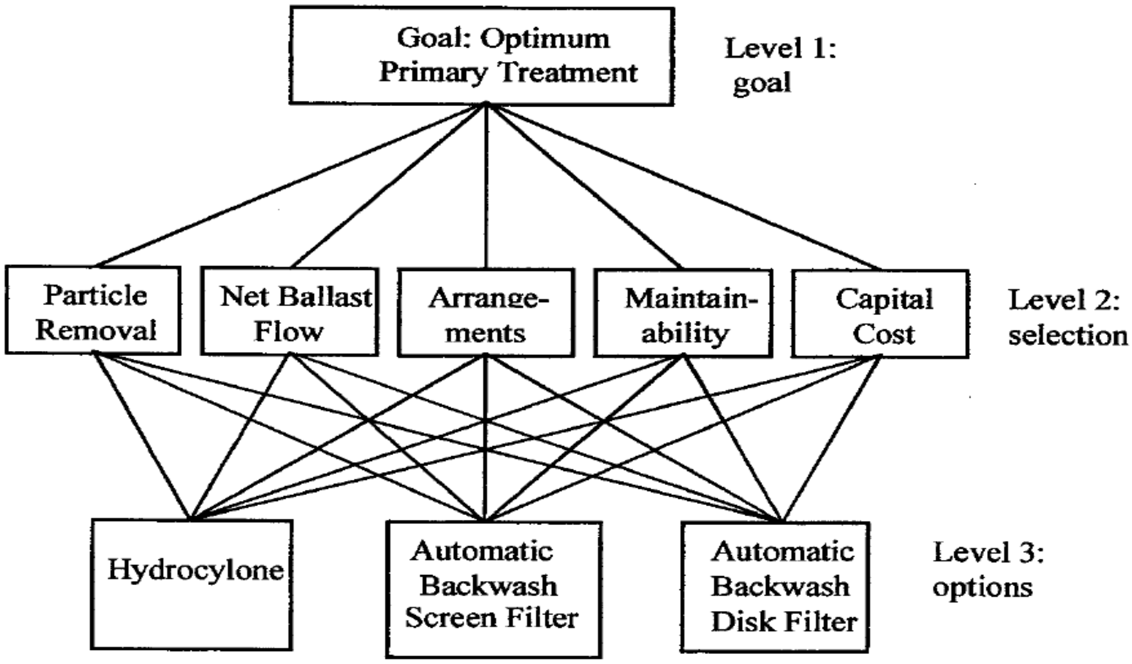


Figure 2-18: AHP model for selecting the primary ballast water treatment system (Parsons, 2003)

In the model, the arrangements criterion is identified when the primary treatment device has various implications such as (weight, footprint and volume). For example, Parsons (2003) assessed that the hydrocyclone was considered to have the smallest volume since it can be positioned vertically and provided the smallest footprint as a significant advantage over the other two filters. The screen type filter was assessed to require a somewhat larger volume arranged with additional two backwash pumps (port and starboard) which its volume requirement would be considered to increase further. The disk filters was assessed to require the greatest addition maintenance to the ballast water system volume. Maintainability criterion identified for the choice of the primary treatment device and its implication on the machinery maintenance and crew workload was considered. Parsons (2003) considered that the hydrocyclone is the lowest because it has no moving parts and thus required no regular crew attention or maintenance except for the internal coating which was considered a low type of maintenance requirement. The screen filter was considered to require more attention and routine (e.g. possible filter screen clogging) and annual type of maintenance (e.g. steam/or detergent cleaning and replacement). The backwash pumps considered to increase the general maintenance requirement. Disk filters, were considered to have much greater maintenance requirements due to the large number of moving parts. The use of external backwash supply was considered to further increase in the system complexity and maintenance requirements. The capital cost criterion was considered to be significant based on the referenced studies there in (Parsons, 2003). Safety was assumed to be appropriately equal for all alternatives. Operating cost was reflected in the net ballast flow and maintainability criteria.

The Analytical Hierarchy Process (AHP) method permits the ranking of discrete decision options and arranged the factors in hierarchy of relationships for the selection of a primary treatment device for a ballast water system. The design decision model problem was structured in three levels. The first level is the goal to select the optimum primary treatment. The second level is the multiple criteria that could be considered. The third level is the three primary treatment options considered i.e. hydrocyclones, automatic backwash screen filters, and automatic backwash disk filters. The AHP uses inputs to the analysis by pairwise comparisons of how the various pairs of criteria contribute to the overall goal or how the various pairs of options contribute to each criterion. The weights can come from engineering data or expert judgment based upon all the hard information and experience available to the user. Both Parsons, 2003 and Richard W. Harkins, co-Project Director of the GLBTDP, jointly made the following judgments based upon their experience from Parsons and Harkins (2002). Parsons (2003) and Richard W. Harkins, co-Project Director of the GLBTDP, judged that particle removal efficiency is absolutely more important than the effect of the net ballast flow to providing primary treatment and the same procedure followed each of the five criteria (one at a time). Parsons (2003) found that disk filter is the optimum primary alternative amongst them. However, it is clear that the weighting process carried is based on the judgment of only two experts in the study. This is because life experience showed that people tend to vary on their judgment and priorities. For example, the experience gained by the two expert based on the study of bulk carrier may not be the same to other types of ships with different type of systems. Therefore, the AHP pairwise comparison between the five criteria may largely vary if the judgments made by more experts from different backgrounds. In addition, there is no sensitivity analysis presented to show how sensitive such a conclusion to the changes of the given weight by this model.

In 2008, a study had investigated the problem with selecting the optimum ballast water treatment systems and utilized the fuzzy sets methodology to perform a comparison among eight ballast water treatment systems namely Filtration, Cyclonic systems, Heat treatment, Chemical treatment, Ultraviolet radiation (UV), Ultrasound , Electroporation, and Radiolysis (Mamlook et al., 2008). The goal of the study was to determine the order in which each of the eight ballast water treatments should be given higher priority to be installed on-board ships, and thus tackle the world wide ballast water selection issue. Also to evaluate the proven technologies and select the best available BWTS with the help of the Fuzzy sets methodology (Mamlook et al., 2008). The eight BWTS alternatives were compared according to their benefit-to-cost ratios by the identified four benefit sub-criteria namely: effectiveness, reliability, global benefits and safety; and four cost sub-criteria namely: capital cost, treatment cost, auxiliary systems, and environmental constraints (Mamlook et al., 2008). These criteria were evaluated based on actual data obtained from the literature referenced in (Mamlook et al., 2008). Based on the results obtained, the filtration treatment appeared as the best method that will provide the best combination of effective treatment according to the considered criteria. The next two options are the use of UV and Ultrasound to produce effective and reliable ballast water treatment in minimum cost and optimum benefits in terms of the identified criteria. They found that the least ballast options are the radiolysis and the chemical treatments due to their high costs and low safety factors (Mamlook et al., 2008). Noting that they normalised benefit-to-cost ratios by dividing the overall fuzzy benefit by the overall fuzzy cost relative weights and compared between the eight BWTS Figure 2-19.

Figure 2-19 shows the obtained benefit to cost ratio for each ballast water treatment system, and the filtration option comes first, followed by UV and Ultrasound (US) i.e. Option I; then cyclonic, heat treatment, and electroporation i.e. Option II; and the least option is radiolysis and chemical treatment i.e. Option III due to their high cost and low safety factor (Mamlook et al., 2008)

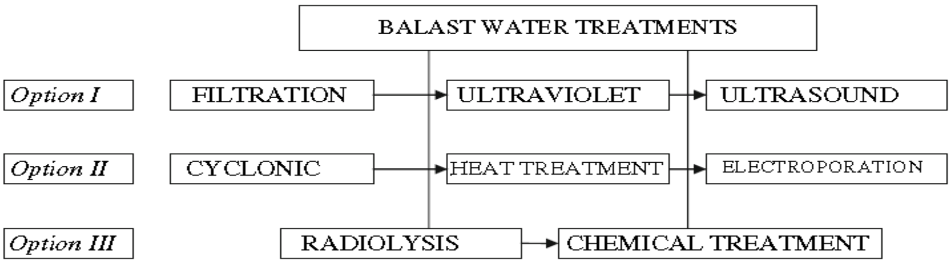


Fig. 4 Hierarchy options for BWT

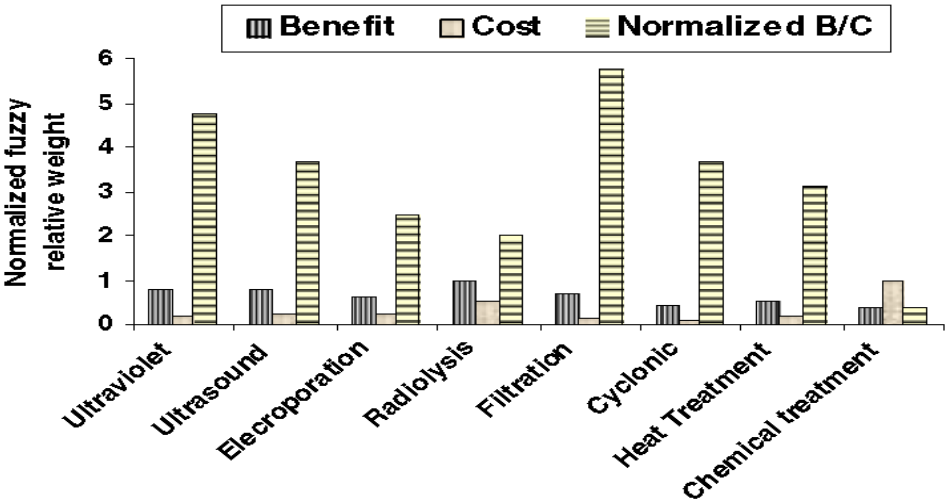


Figure 2-19: Overall results comparison between the costs to benefit ratio (showing filtration as the best option) using the fuzzy set method (Mamlook et al., 2008)

However, the weighting process carried in the study is based on the literature collected data only. The approach ignored expert’s judgments inputs and thus it is not guaranteed that the model is reflecting valid results. The model also neglected the sensitivity analysis of the obtained results by the model and it applicability to sensitive changes on the selected alternative. In addition, the model did not include the ship related criteria in the comparison between the given alternatives. Furthermore, there is no sign of why these particular selected criteria were used by the study and why not other criteria were included?

In 2005, a multi-criteria analysis methodology, using a software named THOR system, was developed to support and guide decision makers in the evaluation and the selection of the best ballast water treatment system (Gomes, 2005). THOR system uses the multi-criteria decision analysis methodology and allows a group of (experts) to reach a decision through the exchange of views within the group members (Gomes, 2005). In order to identify the criteria and obtain preferences, Gomes (2005) followed the following steps:

- Step 1: identify in all proposals submitted by IMO Member States the relevant criteria;

- Step 2: submit this set of criteria to IMO Member States;
- Step 3: obtain the consensus about the criteria set;
- Step 4: identify the alternatives that solve the problem;
- Step 5: submit the alternatives to IMO Member States;
- Step 6: use the THOR module to help the IMO Member States to identify the importance (weight) to criteria;
- Step 7: alternative ordination.

The steps were carried out by incorporating the value of the IMO member states judgments and their preferences to select the best ballast water exchange and treatment methods. Based on the steps followed, five criteria were identified namely: Practicality, Biological effectiveness (including pathogens), Cost/benefits, Time frame within which the standards could be practically implemented, Environment impacts of the process' sub-products (Gomes, 2005). Each criterion was assigned with a number of questions which needed to be analysed using quantitative i.e. nominal scale, to assign a value in a nominal scale, by a value attributed to yes or no answer, or by interval scale or ration scale by IMO members. Questions presented by Gomes (2005) have considered many aspects such as the ballast water system capacity (m^3/hour), risks to the ship's crew, applicability of the system to be used in short voyage i.e. Up to 12 hours, the removal of aquatic organisms and pathogens, cost of installation and operation and fuel consumption, and the generation of sub-products etc. (Gomes, 2005). The system was restricted by two points: (1) the selected (incorporated) system shall not present any unacceptable restrictions; (2) all criteria have the same weight. As a result, the THOR system was able to compare between three ballast water management methods (ballast water methods were kept confidential in the study). Gomes (2005) demonstrated the THOR system ability to select the best ballast water method Figure 2- 20. However, the model's comparison was based on only three ballast water management alternatives and sense difficulties in selecting the best alternative which could be a problem (e.g. what is the difference between 1.038 and 1 in the model?). This could be a substantial point if more than three alternatives are to be considered by this model. Nevertheless, the methodology offers strong basis in terms of identifying criteria and weighting using inputs from experts in the IMO members by involving the decision makers to reflect on the selected criteria through the presented questions under each criterion.

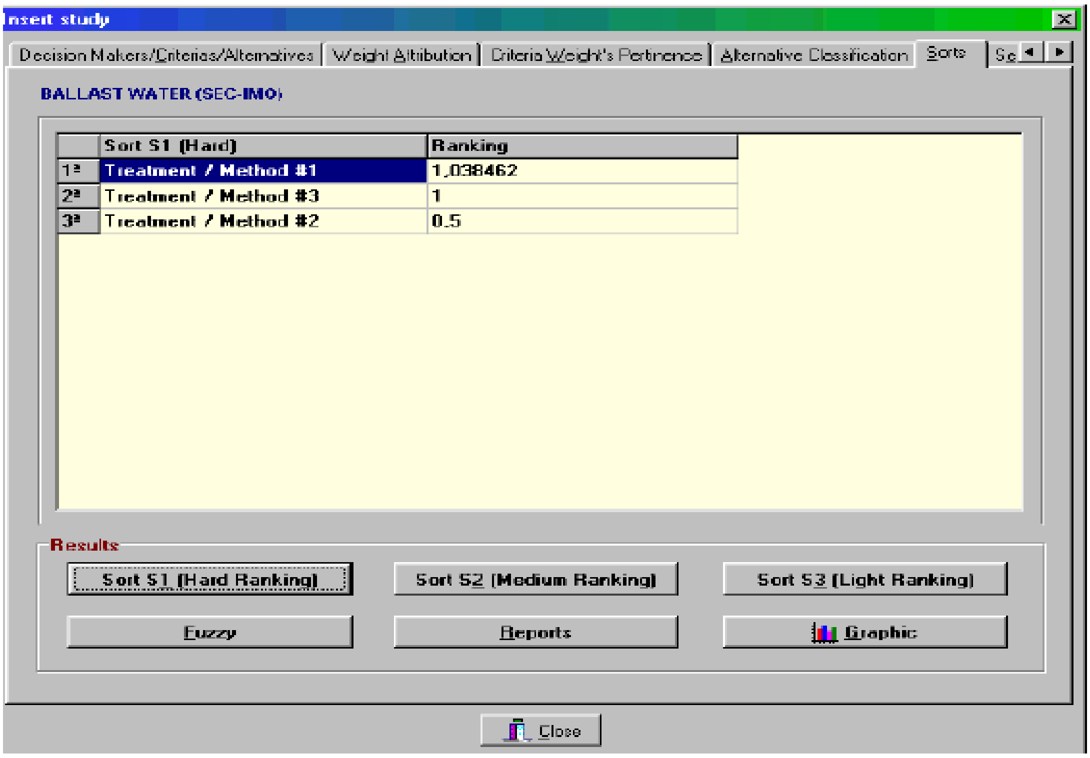


Figure 2-20: THOR's result selected alternative 1 as the best ballast water management method (Gomes, 2005).

However, this approach can be very expensive and time consuming. In addition, the questions were required to be answered by many stakeholders or experts which were not clear how relevant are these questions to the IMO members in order to prevent guessing or misleading answers. The questions had also considered ship related criteria, but did not allow such criteria to have different weights by the decision makers. The study also lacked the applications of the importance to carry out sensitivity analysis in order to evaluate how sensitive are the results to the possible subjective or objective errors.

In 2012, a comparison study between three ballast water treatment units namely filter unit, ultraviolet (UV) unit, El-Chem unit were evaluated from the sustainability point of view in order to guide decision makers to select the most sustainable ballast water technology (Basurko and Mesbahi, 2012). Basurko and Mesbahi (2012) developed a model which is based on three sustainability indices for the comparison and trade off assessments namely: Environmental sustainability, Economic Sustainability and Social sustainability. The methodology collates the latter to obtain a single measure of sustainability. Methods such as Life Cycle Analysis (LCA), Environmental Impact Assessment, Life Cycle Costing (LCC) or Net Present Value (NPV), cost-benefit analysis, questionnaires were selected in modelling the sustainability performance indices through the use of intelligent algorithms to provide quantitative measures for environment and economic parameters. On the other hand, a new method is used to evaluate the social sustainability, enabling the quantitative integration of all the three indices, and then all the three individual indices are combined to provide a single performance index of sustainability of the given ballast water alternatives. For example, environmental sustainability index obtained by assessment using the LCA method; economic sustainability index was obtained by assessment using the LCC method (taking account of two factors: (1) cost of each material and transportation mode, (2) amount of different material required and distance) and social sustainability index were derived from BAMES tool developed by (Cabezas-Basurko, 2010). BAMES tool inspired by Myers-Brigges Type indicator (MBTI) where personality comes described in four letter codes with a resulting 16 personality type in order to reflect the social impacts sustainability (for more information see Cabezas-Basurko (2010)). All three obtained indices are summed and normalised in order to obtain one single score (ranging from 0-100) representing sustainability performance of a ballast water technology Figure 2- 21. The developed tool by Basurko and Mesbahi (2012) were able to compare between the ballast water options through computing the index of sustainability and presenting the results within a 0-100 range i.e. 100 refers to the major impacts and 0 to the least impact. Basurko and Mesbahi, (2012) found that UV unit is the least sustainable alternative (scoring 82.6), then El-Chem unit (scoring 70.6) and the most sustainable alternative is the filter unit (scoring 8.5). UV unit was also found to be the least environmentally friendly while El-Chem unit appeared to be the most expensive amongst the three alternatives (Basurko and Mesbahi, 2012).

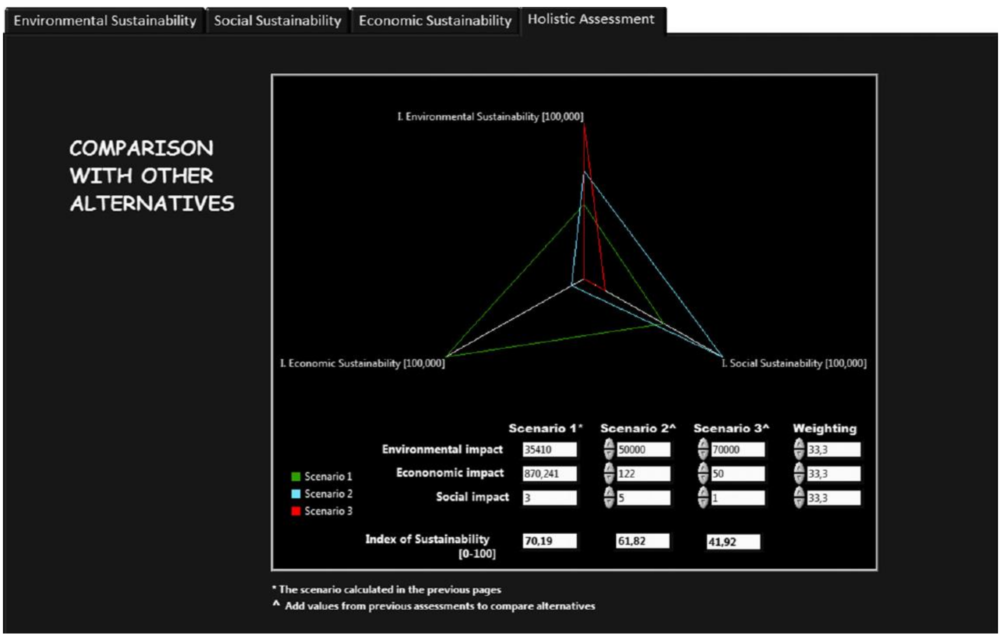


Figure 2-21: appearance of the developed intelligence tool for sustainability comparison between three ballast water management options (Basurko and Mesbahi, 2012)

Acknowledging the usefulness of the methodology. However, it was noted with several weaknesses. Obtaining a sustainability index by utilising the LCA and LCC and environmental impacts focused greatly on the material, cost, and impacts between each ballast water option for the selection between the alternatives and overlooked other important factors such as (biological efficacy, practicality to the ship, safety to ship's structure and crew, objectives of each ship-owner or operator etc.). In addition, this model did not show why only such criteria were selected for the comparisons, and no inputs from experts on the defined criteria was shown. The study did not perform sensitivity analysis as it was not able because each index is obtained individually as acknowledged by the study. Final note is that this model is focused on the cost-benefit and environmental and social impacts and completely neglected the other important parts of the equation in matching these options with the different ship related criteria.

In 2014, a study utilised the Life Cycle Assessment (LCA) and cost-benefit methods in order to evidence the advantages of using the LCA methodology as a tool to shipboard and maritime industry operations. The study compared between three IMO approved multi-components ballast water treatments namely: technology A: ultraviolet (UV), technology B: cavitation, and technology C: Deoxygenation (Blanco-Davis and Zhou, 2014). The study considered the impacts of the BWTSs on the environment with reference to the carbon and stainless steel, plastic in addition to the cost-benefit analysis. Blanco-Davis and Zhou (2014), found that technology C as the least environmentally effective and reasoned this due to the bigger size in terms of materials, fuel and processed water consumption than the other two alternatives. Technology A has been found to score higher than the other two alternatives in emissions to air and this was reasoned due to the high energy consumption for typical UV system. Technology B was found to be more environmentally efficient compare to the other two alternatives. On the other hand, assessing the three technologies with regards to cost-benefit analysis, technology A was found to be the most expensive to install and maintain over the 25 years. Technology C was found to 25% more economical than technology A but 13% more expensive than technology B. Based on aggregating the latter information with the environmental results. Blanco-Davis and Zhou (2014) concluded that the best option between these three systems has turned out to be technology B for the given bulk carrier. Acknowledging the LCA model with the cost-benefit aggregations, however, it appears that the model lacks many issues for several reasons. Firstly, it is obvious that LCA tool is greatly focused on the environmental impacts only, in a less similar way as Basurko and Mesbahi

(2012) for the ballast water treatment (e.g. renewable resources, emissions air/water/soil etc.) rather than considering other important factors such as the biological efficacy, process time, and influence on the operation of a ship. Secondly, the methodology seems to neglect subjective parameters such as safety, health issues in the final decision. There is no sensitivity analysis carried out in the study in order to test the possible errors to the selected ballast water treatment alternative. From environmental concerns technology C is the least environmentally friendly as found by the model. The question is why it would not be the same case for a different ship?

In 2012, Jing et al (2012) highlighted particularly the unpredictable weather conditions and harsh environments which may potentially affect the applicability and the feasibility of ballast water treatment technologies. Jing et al (2012) proposed a risk based fuzzy-stochastic-interval programming decision support system in order to help adjust the operating factors and support sound decisions and act to mitigate negative impacts and particularly concerns in the harsh environment. The proposed system initiates at selecting the best available treatment technology by adopting a Fuzzy-Stochastic Analytical Hierarchy Process (FSAHP) method to adjust the operating factors and support sound decisions and actions Figure 2-22 (Jing et al., 2012).
Figure 2-22 shows that the model is focused on optimizing and adjusting treatments parameters (e.g. UV dose, ozone concentration, heating temperature) with the changes of climatic changes such as in a freezing environment in such an integrated way to provide optimum operating factors (e.g. treatment dose, operating time, flow rate). The developed model shows a promising way to achieve the best trade-off between cost, risk and efficiency. The proposed method is expected to generate the optimal system adjustments based on the ambient conditions and predefined objectives (e.g., risk, efficiency, policy, and cost) for supporting decisions on how to treat and manage ballast water to eliminate harmful organisms and meet the international regulations discharge standards while mixing benefit-cost ratio in harsh environments and under changing climatic conditions. However, the model is not focused on the selection of the best BWTS alternative rather that it has touched on a way to optimise the operation of a ballast water treatment system to the changing climatic conditions. Other studies considered developing decision support model in ballast water management such as the “risk assessment approach” developed by (David et al., 2014). However these decision models did not consider the selection of the best BWTS, they

focused on assisting the Port State Control (PSC) inspections on compliance or non-compliance of the calling ships.

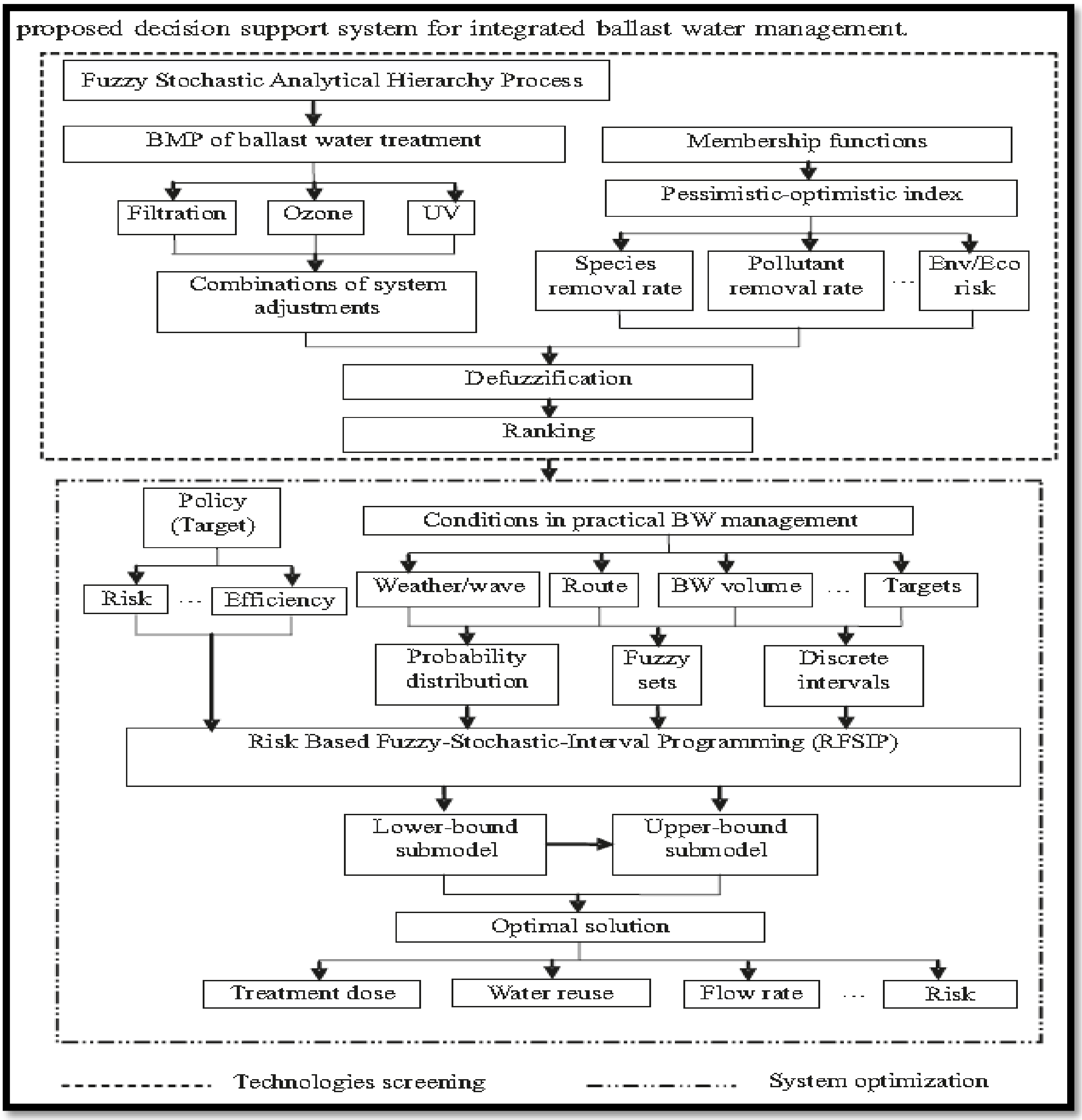


Figure 2-22: Framework of the proposed decision support system for integrated ballast water management (Jing et al., 2012)

In 2013, a comparison study between five ballast water treatment alternative namely Heat treatment, Ultraviolet (UV), Ozone, Ultrasound and Biocide has been carried out (Jing et al., 2013). The methodology utilised hybrid Fuzzy-Stochastic Analytical Hierarchy Process (FSAHP) with the integrated beta-PERT distribution, fuzzy set theory, and pairwise comparison by Monte Carlo simulation into their model. The ballast water treatment alternatives were compared based on several criteria namely efficacy on micro-organisms, efficiency on organic, adaptability to harsh environment, capital cost, O&M cost, human risk, ecological risk, waste production Figure 2-23 (Jing et al., 2013). Figure 2-23 shows the model and the goal of the model was to select the best on-board treatment technology in order to eliminate invasive microorganisms and to remove water soluble organics from ballast water, particularly in the harsh environments. Inputs of judgments data about each alternative were obtained by nine local experts from governmental ministries i.e. environmental division and academic institutions i.e. professors and graduate students at *Memorial University of Newfoundland* through rating the performance of each ballast water treatment alternative and the importance of each criterion using the linguistic scales provided in (Jing et al., 2013). The obtained results and statistics following the proposed FSAHP approach were carried out.

Jing et al (2013) found that the heat treatment to be the most attractive solution in terms of the lowest health risk followed by the ozone treatment with respect to the human health risk. Ultrasound, biocide and UV were noted as the least preferable option with considerable overlaps between each other.

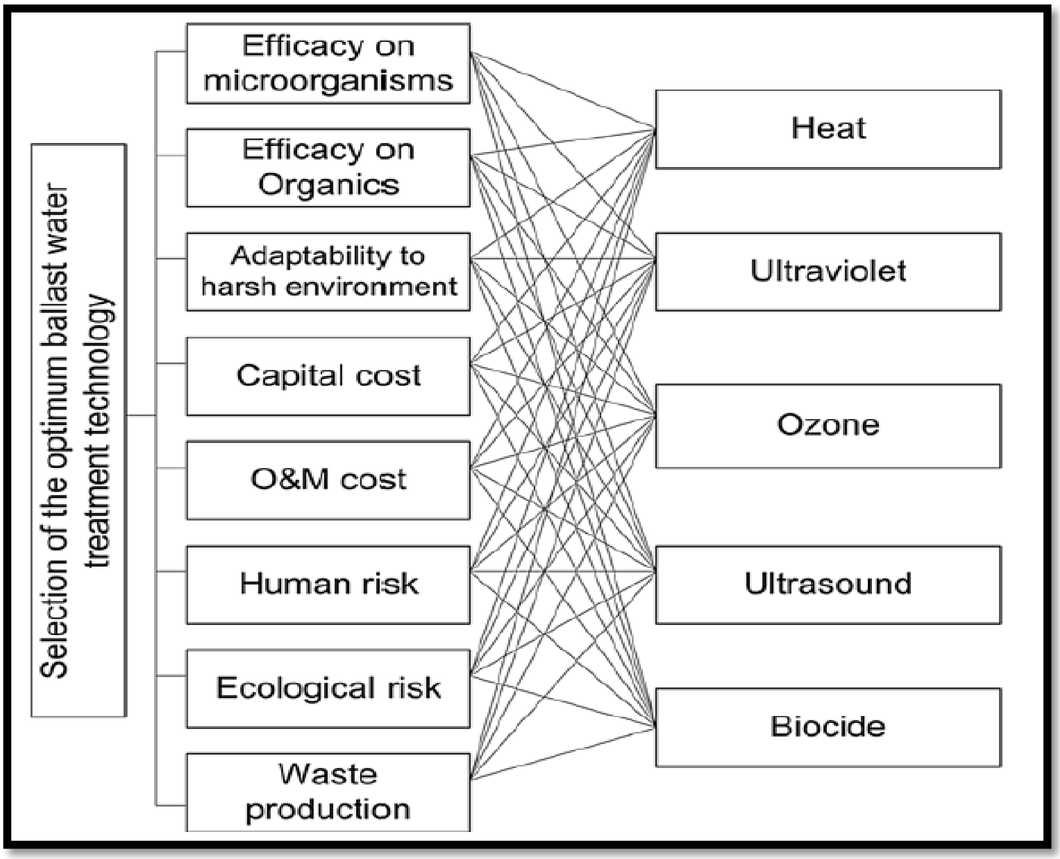


Figure 2-23: Hierarchy structure of the ballast water treatment technology selection problem (Jing et al., 2013)

This overlaps were explained as the low confidence by the experts in ranking between the alternatives. On the other hand, Jing et al (2013) supported his findings by carrying a statistical test which rejected the null test that heat treatment was not the probabilistic optimal alternative (versus that it is) with a level exceeded 95% indicating that heat treatment is the lowest health risk compared with other alternatives (e.g. ozone). Jing et al (2013) found that the UV treatment was ranked with highest overall score and this was also statistically confirmed as well. The ozone was ranked the second (61-71.4% confidence levels), heat treatment was ranked as the third (56-68.4% confidence levels), ultrasound treatment was ranked as the fourth (78.4-84.6% confidence levels), and last option was the biocide (Jing et al., 2013).

Acknowledging efforts of the developed model; however, the model considered the efficacy of the ballast water treatment on microorganisms and organic and lacked to take into account the ship related criteria and ship safety which isn't clear how they were considered by the model. The inputs of judgments by the experts can help in identifying the performance of each BWTS alternative but can't be relevant to other judgment related to the ship as a key factor for the selection. The sensitivity analysis was not carried by the study in order to check the most critical criterion and the change of the results in case of errors.

In early June 2014, a study on BWTS selection procedure for conventional merchant ships based on the financial, legal and operational circumstances has been published (Satir, 2014). Satir, (2014) investigated the role of the BWTSs and developed a Generic Fuzzy Analytic Hierarchy Process (G-FAHP) for the selection procedure for the conventional ships. Satir (2014) investigated the BWTS selection problem through a sample of existing five ballast water management systems products and two candidate ships i.e. 15,000 dwt handysize bulk carrier (10 years old) and 120,000 dwt aframax oil tanker (new building ship). Satir (2014) used these two ships for exposing trade-off between an existing hull and a building project and a small-size bull carrier and a huge oil carrier using the G-FAHP. For defining the criteria, Satir (2014), conducted a group discussion to evaluate and finalise the criteria for the problem. The group discussion contended nineteen researchers in the field and four practitioners in shipping business gathered for a brainstorming session and completing a pairwise comparison survey at an academic workshop-Informa 2012 in London. As a result of the discussion, the BWTS selection problem is designed in three factors namely: cost, technique, and legal basis Figure 2-24. The Cost is divided into: installation cost (INSC) and operational expenses (OPEX).

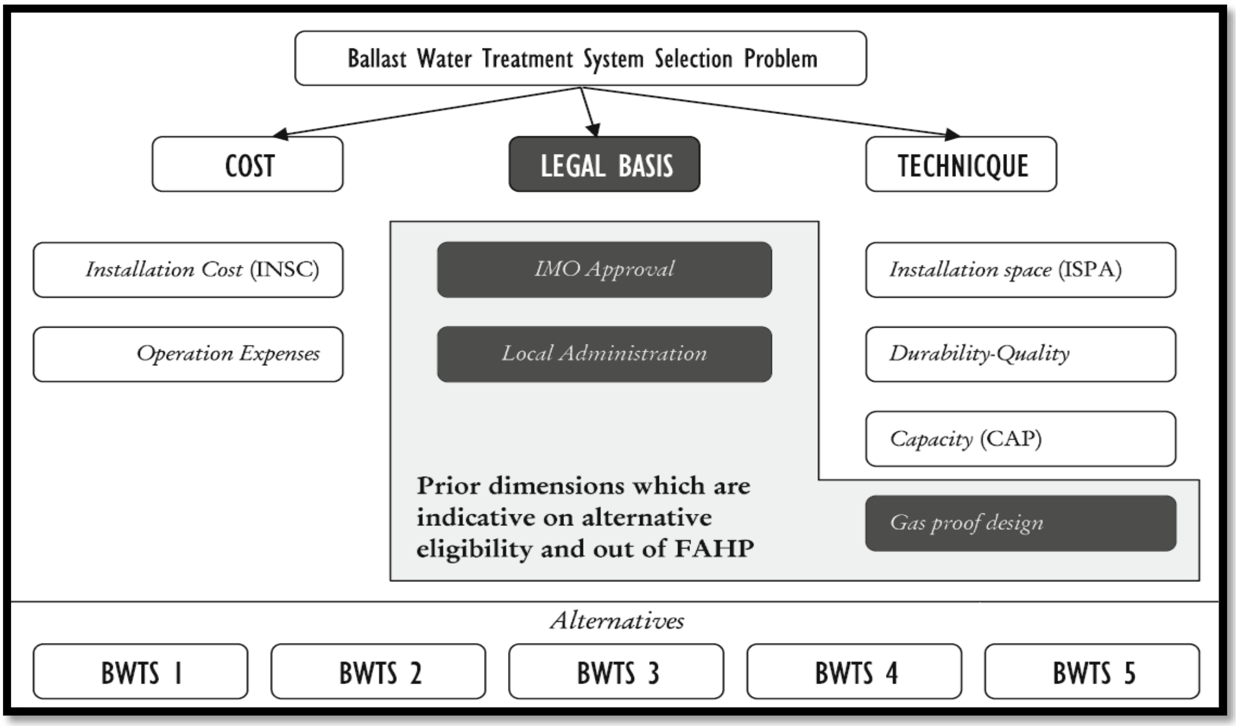


Figure 2-24: The GFAHP Decision hierarchy of ballast water treatment system (BWTS) selection problem (Satir, 2014).

Legal basis is divided into IMO approved and administration approved because only active substance BWTS requires an IMO approval. The technique is focused on the particular of the BWTS through the space limitation, operating time, system failure probability, capacity of the system and gas-proof insulation on the devices (Satir, 2014). These criteria were weighted by seven decision makers from shipyards industry, shipping company, and ship port authority. Satir (2014) found that installation cost as the most important criterion (0.56) and the next important criterion is the OPEX (0.44) for the selection of the proper BWTS. Satir (2014) also found durability quality and capacity criterion weighted the same (0.39) and space has the lowest weight (0.22). Satir (2014) compared all the BWTS alternatives with each other and dry bulk carrier and aframax tanker for the selection of the proper BWTS. The model, selected BWTS1 for both ships because BWTS1is found superior to other BWTSs with regards to the defined criteria (Satir, 2014).

Acknowledging the robustness of the model in terms of defining the criteria used and the inputs by the experts, however it is not clear from the study if the ship related criteria were considered. This is because the voyage length, for example, and geographic location of the ships may influence the selection and they were not considered by the model. In addition it is not clear how the limited space criterion appeared less weighted particularly if small ships and ship-owners may not agree with such findings and thus such an approach should be consider on a single base finding rather than a generic one.

2.4 The problem statement in the selection of a ballast water treatment system models

There are many different treatment technologies available today, and most of them were already used for municipal and other applications. For example, David et al (2014), collected about 104 different ballast water management system; however, based on the literature, we can no longer ignore the fact when applying those treatments to the ballast water purpose, none have shown the capability to achieve the required IMO regulation D-2 standard.

It should be noted that, some of these systems will not be commercially ready because manufacturers may have stopped the development or withdrawn their systems from the market. Therefore, these developments of BWTS are very dynamic in the market with newly proposed promising systems. In addition, from the literature, these BWTS varied in their capacities which range from 50 m^3 per hour to more than 10,000 per hour; the combination of technologies; the treatment process i.e. at the uptake of the ballast water, during the holding of the ballast water in tanks or/and at discharge; type approval obtained etc. (David et al.,2014). "*According to calculation made by Japanese experts who calculated the number of ships which the regulation D-2 would have been implemented as planned originally from 2009 to 2020. The number of ships would have totalled to more than 75,000 ships, with the highest annual number in 2017,i.e. more than 16,000 ships divided by 365 day per year, this results in an installation demand of 45 BWTS per day"* (David et al.,2014). Moreover, a preliminary cost estimates were presented in 2009 Marine Environment Resource Centre (MERC) and concluded a value of global market for purchasing and installing BWTS between 2011 and 2016 will be in the value range of US$ 50 to 74 billion (King et al., 2012).

The review of the developed models showed that the selection of ballast water treatment systems are both important and feasible approach to minimise risks with such a complex decision. Unfortunately, there is a small and very critical issue with the previous models such as the variation of the criteria which should be used from the selection between BWTS. In any given model, one of the most important and critical factor is capturing the required information and making the necessary evaluations in order to generate the expected output which can only be possible by identifying these important/critical criteria. Under the situation where a model neglects a particular criterion, it will invariably lead to a deviated output or making a wrong selection which can be very significant. Therefore, the need to identify the parameters and/or the criteria to select the most feasible ballast water treatment is a very important step. On the other hand, the selection of the required stakeholders who are directly confronted with the selection problem such as shipping companies was neglected or have not been given sufficient weight in the previous models. Therefore, involvement and exploration of decision makers from shipping companies are also very important steps for collating their expert views and opinions on the selection issue, the existence of the models used, and the importance of criteria that should be considered by a decision model.

These gaps raise the key question: *How can we better investigate the issue with the BWTS selection?* In order to answer this question, the aim of this PhD thesis is to develop a decision support tool to help decision makers in shipping companies (ship-owners / operators) to select the most feasible BWTS for their ships. To achieve this aim, the objectives of this PhD study are listed as follows:

1. To identify the influencing parameters and/or criteria related to both ballast water treatment system and ships parameters.
2. To evaluate the importance of the selected criteria for both BWTS and ship parameters criteria.
3. To apply an appropriate Multi-Criteria Decision Making (MCDM) technique along with the above points.
4. To validate the develop decision support tool and investigate its applicability in actual case studies.

2.5 Summary

- This chapter provides an overview of the background of ship's ballast water definition, operation, capacity, bio-invasion and its potential associated impacts and finally ballast water convention (regulation and standards) were also discussed.
- This chapter reviewed the international regulation and the various ways of ballast water management aiming to presents each approach strength and weaknesses.
- The chapter noted that there many influencing parameters which have been identified as influencing parameters for each type of ballast water management. Consequently,

randomly selecting any ballast water management (or combination) to fit any type of ship do not seem a proper way.

- This chapter outlined the background and key differences between the marine vehicles and their wide divisions. The seagoing marine vehicles can also be divided again into transporters (e.g. passenger, general cargo and bulk cargo) and non-transporters (e.g. fishing, military etc.). Transporters marine vehicles again were divided into a number of broad categories. Differences between the different seagoing marine vehicles were highlighted.
- This chapter provided a critical review of the relevant studies that investigated the issue with the BWTS selection. However, several issues or gaps were noted in the literature:
    - They varied in their approaches and methodologies;
    - They varied in their chosen criteria for comparing between the alternatives;
    - Shipping companies or operators has been neglected or have not been given sufficient weight (as a key player who is faced with the selections issue), to be involved in the previous models;
    - Ship related criteria has been neglected or not given sufficient weight to the fact that ships also varies in their characteristic and thus no study or less studies considered ship related criteria in previous model.
- These gaps raise the key question: *How can we better investigate the issue with the BWTS selection?* In order to answer this question, *the aim* of this PhD thesis is to develop a decision support tool to help decision makers in shipping companies (ship-owners / operators) to select the most feasible BWTS for their ships. To achieve this aim, the objectives of this PhD study are listed as follows:

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4. To validate the develop decision support tool and investigate its applicability in actual case studies.

Achieving these objectives will enable the achievement of the ultimate aim of this PhD thesis.

Chapter 3 will provide over view on the research methodology, research design, Multiple-Criteria Decision Making (MCDM) and the details steps of the developed AHP model and its procedure.

Chapter 3: Research Methodology

3.0 Introduction

This chapter provides an account of the author's considerations with regard to the selection of the appropriate methodology and the overall research design for this study. It considers the different aspects of research methodology, paradigm (qualitative or quantitative or both) and researcher's assumptions.

This chapter considers how this research with a schematic flowchart is designed. Thereafter, it explains why The Analytic Hierarchy Process (AHP) method has been chosen. The latter was based on comparing the similarities between the two most widely used type of value measurement models which are the Multi-Attribute Value (or utility) theory (MAVT or MAUT) by Keeney and Raiffa (1976) and The Analytic Hierarchy Process (AHP) by Saaty (1980). This chapter compares similarities between the two methods before concluding that AHP fits the purpose of this research study.

The decision support tool is developed to help decision makers to evaluate and select between given ballast water treatment systems (BWTS) for their ships. This step have been derived based on the gaps from the literature in chapter 2. Finally, this chapter also discusses the popularity of AHP method with the focus to justify its capability as MCDM method for solving the identified problem of this research study before it gives details of the steps and how the developed AHP method is used.

3.1 Research Methodology

The purposes of any research are normally identified and classified by the researcher according to his/her chosen research problem, the research questions, and the paradigms under investigation. The characteristics of a particular issue or problem, and the purposes of the research questions reflect the research problem and can classify the research as exploratory, descriptive, analytical or predictive. Methodologies are like theories that cannot be verified or falsified, but are nevertheless more or less useful (Collis and Hussey, 2003). There are many different types of research design, and many methodologies. They often lend themselves to a paradigm, depending on the researcher's assumptions (Hussey and Hussey, 1997, Collis and Hussey, 2003). A 'Paradigm' refers to the progress of scientific practice based on people's philosophies, assumptions about the world, and on the nature of knowledge. In this context this will influence how a given research study is conducted (Collis and Hussey, 2003, Hussey and Hussey, 1997). The researcher's adopted paradigm can be based on positivist paradigm "quantitative" or phenomenological paradigm "qualitative" or both. The qualitative approach is descriptive in nature with the findings described by words or pictures. On the other hand, the quantitative approach is defined by numerical findings Figure 3-1.

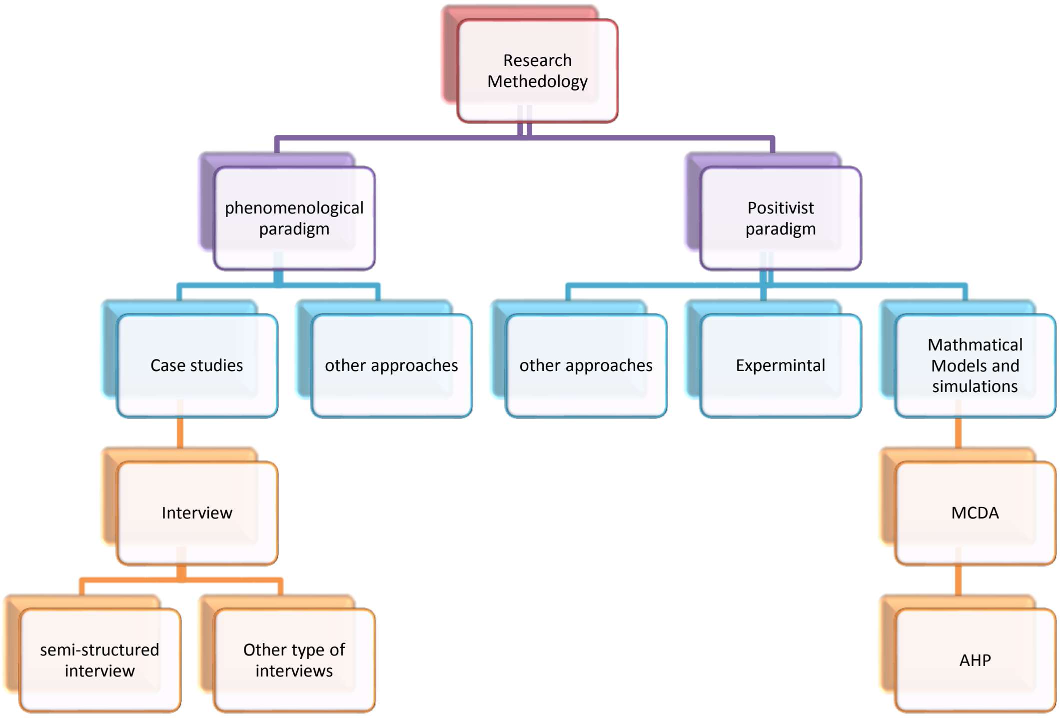

Figure 3-1: Research methodology

Consequently, each type of study uses different strategies of presentation in order to project divergent assumption about the world and the different means to persuade the reader of its conclusions (AI-Qattan, 2008). This is because researcher's ontological, epistemological, and axiological assumptions have a significant influence upon their adopted paradigms (e.g. positivist or phenomenological), and consequently on the research methodology utilised.

AI-Qattan (2008) listed four differences that often found between the two extreme paradigms (quantitative or qualitative) on their analysis of a given research:

1. *Assumptions about the world.* The quantitative researcher is based on positivist philosophy's assumption that social facts have an objective reality that is independent of the beliefs of individuals. On the other hand, qualitative research is based on

phenomenological paradigm's philosophy beliefs that reality is socially and that it is only understood by examining the perceptions of human factor (Collis and Hussey, 2003).

2. *Purpose.* Quantitative research seeks to explain the causes of changes in social facts, fundamentally through objective type of measurement and quantitative analysis. On the other hand, qualitative research is more concerned with the understanding of the social phenomenon based on the actors' perceptions and this is done through participating in the life of those actors.
3. *Approach.* The quantitative researcher often employs experimental or correlational models in order to reduce error, bias, and other 'noise' that keeps one from clearly perceiving social facts. On the other hand, qualitative researcher looks for depth of information in relate to the phenomena if interest.
4. *Researcher role.* The ideal quantitative researcher is often detached from the data he observes in order to avoid bias. On the other hand, qualitative researcher is typically 'immersed' in the phenomenon of interest.

Based on the above differences, qualitative and quantitative approach may seem to be conflicting and are derived from different philosophical views, yet they both form strong bases of effective research. For example, the importance of the latter point is strongly emphasised in the literature, not to argue whether a quantitative research approach should be replaced by qualitative research or vice versa, but both forms of research are much needed since all research questions cannot be solved with the same approach (Näslund, 2002).

Recall the research aim of this study is to *develop a decision support tool* to aid decision maker, i.e. ship owners/operators to select the most feasible BWTS for their ships. Therefore, utilising a mixture of a qualitative approach, i.e. case study and interviews and quantitative approach, i.e. developing a mathematical model, in this research are found more appropriate in order to incorporate various aspects and gain more accurate and precise understanding to meet the aim of this study.

3.2 Research design

The research design must be directed by the literature review and framed by appropriate and selected methodologies. Figure 3-2 presents a schematic flowchart of how the research is designed.

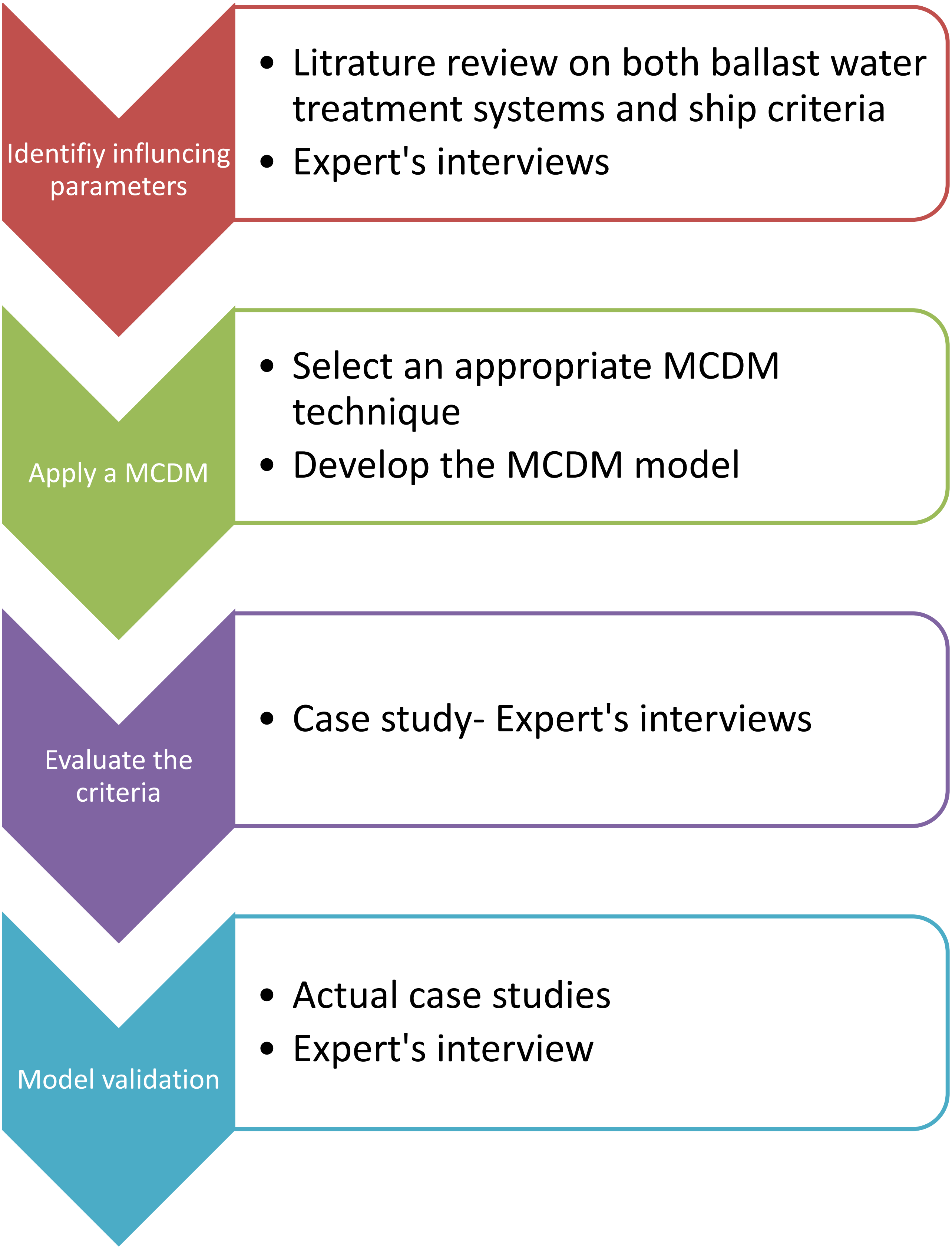

Figure 3-2: Research design

To summarise the steps in Figure 3-2 as follows:

- The first is to identify the influencing parameters related to both ballast water treatment system and ship parameters as discussed in chapter 2.
- One of the popular discrete type Multi-Criteria Decision Analysis (MCDA) known as the Analytical Hierarchy Process (AHP) method was used to develop a decision tool model that decompose the identified criteria in order to select the most feasible ballast water treatment system (BWTS) for a given ship. The AHP method was used in this study because it is an approved powerful tool that can be used to make decisions in situations where multiple criteria or objectives are present. Although other methods may be used, the AHP method is used for quoting Gass (2005) "*AHP is theoretically sound, readily understood, easily implemented, and capable of producing results that agree with expectations*" (Gass, 2005).
- An application of a case study through interviews was conducted with twelve experts from shipping companies to seek more understanding of the shipping companies' opinions with regards to the identified criteria that should be considered when selecting between given BWTS alternatives for their ships. Therefore, a qualitative approach though interviews was adopted in a case study with twelve senior staff and managers from three different size and trade interest shipping companies. The interview approach is chosen because it generally aims to gain depth of information, opinions or particular knowledge about a phenomenon such as the decision makers inside these shipping companies who are aware of it or has some data related to it. Therefore the face-to-face interview with senior staff and managers "decision maker's personnel" or experts was found as an appropriate approach to enable the researcher to obtain more depth of information from the direct experience of interviewees. The experts have identified and evaluated the importance of each criterion and added more, thus validated the criteria used in the developed AHP decision support tool based on their experience.
- Finally, the important identified criteria were utilised in the developed mathematical decision tool or model in actual case study. A validation was based on actual case studies and expert's interview.

3.2.1 Case Study

"*A case study is an extensive examination of a single instance of a phenomenon of interest and is an example of a phenomenological methodology*." (Collis and Hussey, 2003). Generally a case study approach implies a single unit of analysis, such as one shipping company or one ship, in which it involves gathering detailed information about the unit of analysis over a period of time with the aim of obtaining in depth understanding of the phenomenon. According to Collis and Hussey (2003), a case study may be limited to just a few aspects of an organisation; however, the results can be extremely stimulating and original. Methods that are often used in case studies can include documentary analysis, interviews and observation which requires the researcher to be careful with the ethical issues associated with such approach.

In this research, a case study used in the sense of its application in order to analyse the empirical and theoretical evidence from shipping companies by conducting interviews with experts involved in the phenomenon under the investigation of this study.

3.2.2 Ethical issues

Ethical issues are very important in research which involves participants. The ethical principal is divided into areas such as: whether there is harm to participants; lack of informed consent; invasion of privacy or confidentiality; deception is involved (Bryman and Bell, 2011). Please note that in this research we did not need to do anything with participant's privacy or any physical involvement, but their expert opinions on technical matters were needed for the purpose of this research. Therefore, no privacy or confidential information was required. A careful consideration was given to the list below in connection with ethical issues (Song, 2011):

- "No prospect of any harm coming to the participants.
- Participant must understand the goal of the research.
- What the research is about? (purpose of the research)
- The nature of their involvement?
- Length of the time needed?
- Their involvement is voluntary and can withdraw at any time.
- What will happen to their answers or data collected?
- Privacy and confidentiality of data and participants must not be violated.

- Participant must not be deceived.
- Names of participants and their company are confidential
- The locations of the research are identified".

The above consideration matters were carefully followed.

3.2.3 Interviews

"Interview is one approach of collecting primary data, in which a participant is asked questions in order to find out what they do, think or feel." (Collis and Hussey, 2003)
Interviews can be conducted through face-to-face, voice-to-voice, or screen-to-screen and can be conducted with individuals or a group of individuals. The aim of the interview is to collect valid and reliable information through recording data and observations. Types of interview may include (e.g. structured interview, semi-structured interview, unstructured interview, focus group type) that all vary in their style, structure and the formality of the questions asked.

In semi-structured and unstructured interviews, the issues are discussed and new questions may be raised which facilitate the matter to be explored can change from one interview to the next as different aspects of the topic are revealed. This process of open discovery is the strength of such type of interviews. However, there is risk if time is consumed in one question rather than moving to the next one in unstructured interview more than that in a semi-structured type.

Therefore, in this study, face-to-face interviews were used, and the interviews were semi structured with limited open questions. The open questions differs from the closed questions as the former offers the advantage that the respondents are able to give their opinions as precisely as possible in their own words. Whist the latter only limit the respondent with selecting between numbers of predetermined alternatives. As a result, this approach provides the interviewees the flexibility and time to articulate and clarify their answers and responses. This type of interview was conducted with high rank staff and managers whose knowledge and experience were very beneficial to achieve the research's aim and provided valuable information.

3.2.4 Recording data and observations

Recording data and observations can be done by using a prepared record sheet, or by taking notes or using an audio cassette or a video. In most cases the data thus recorded will be qualitative.

In this study, data were recorded by taking notes during the interviews. The advantage of note taking over recording qualitative data is that you can record your observations and responses to questions immediately. In addition, when writing your notes you are automatically screening and summarising the information. This is because it means that you have already begun to analyse your data. However, the disadvantages of note taking is the time consumed while taking notes which it may mean that the researcher is more concentrating on taking notes rather than paying attention to other aspects, such as attitude, performance and body language.

3.3 Data Analysis

The main challenge to *qualitative data analysis* is that there is "*no clear and accepted set of conventions for analysis corresponding to those observed with qualitative data"* (Robson, 1993, p. 370) there in (Collis and Hussey, 2003, p.253).

Analysing data can be determined by the type of data collected i.e. is quantitative "numerical" or qualitative "textual". For example, quantitative data are generally analysed using the used statistical techniques such as such as Minitab or SPSS (Statistical Package for the Social Sciences), or a spreadsheet program, such as Excel. These computer programs enable a wide range of analysis, carry out statistical tests quickly and accurately and present the results in the form of tables or charts for interpreting the data collected.

Phenomenologists approach often collect qualitative data. Data analyses consist of three main activities, i.e., data reduction, structure, and detextualise the data. According to Collis and Hussey (2003) there are two main methods for analysing qualitative data, i.e. quantifying methods such as content analysis, formal methods, informal method; and non-quantifying methods such as general analytical procedure, data displays, and grounded theory.

The general analytical method through the narrative text display and interpretive approach are one of the methods of data analysis to understand the information experienced by people who were interviewed. Narrative text is one of the common modes of data display in qualitative research as an attractive approach for bridging gaps between theory and practice.

A mathematical AHP model for selecting the most feasible ballast water treatment system for a given ship was used in analysing data in this study. To validate the model, the importance to include or not to include criteria which is more or less significant was identified based on expert's experience dealing with the selection problem. The validation of the criteria used is equally important as the developed decision support tool. In addition, the interpretative approach was also used to validate the applicability and the validity of the model through experts interviews on the outcome or the results derived.

Therefore, in this study, the AHP model and the general analytical method through the narrative text display and interpretive approach were used to analyse the collected data.

3.4 Multi-Criteria-Decision-Making (MCDM)

Multiple-Criteria-Decision-Making (MCDM) is a sub-discipline of operations research or operational research (OR) that explicitly considers multiple criteria in decision-making environments in order to provide the optimum solution to aid decision maker's planning.

According to Belton and Stewart (2002), a *criterion* implies some sort of a *standard* by which one particular choice or course of action could be judged to be more desirable than another. Therefore Belton and Stewart (2002) defined such activity by the following quotation: *"consideration of different choices or courses of action becomes a multiple criteria decision making (MCDM) problem when there exist a number of such standards to a substantial extent."* And Belton and Stewart (2002) defined the activity of selecting a decision making method as a Multiple-Criteria-Decision-Analysis (MCDA) as follows: *"the collection of formal methods that are able to take into account multiple-criteria in helping decision makers or individual or groups explore decisions that matter to them"*. This implies that MCDM or MCDA are the same thing but are often named differently by different authors. According to an MCDA expert: *"the difference between MCDA and MCDM is more a philosophical in which "M"= making and implies finding the right answer; where "A"= analysis and is more about the process".*

After defining the MCDA above, in this section we focus on how MCDM or MCDA is identified and when can it be considered important to utilise, its purpose, and what is expected from it next.

According to Belton and Stewart (2002), in every decision we take will require a multiple factors named *criteria* which sometimes are explicit or implicit in a sense that everyone is consciously well practicing MCDM in everyday life. However, the demand for developing a MCDM model or tool is not required, unless the significance of the following criteria in according to Belton and Stewart (2002) exists:

- The problem is too complex and has a conflicting nature imbedded;
- The consequences of things went wrong are substantial and cannot be easily remedied;
- Solving the problem maters is important to a great deal;
- The problem can change with time.

Therefore, MCDM aims to help decision makers organise and synthesize complex information in a way which leads them to:

a) A more tolerable confidence about a decision;
b) Minimise the potential for post decision regrets by satisfying all criteria or factors which was taken into account.

Belton and Stewart (2002) explained that the expected myths from utilising MCDA as follows:

1. MCDA will not give the right answer. This is because the concept of optimisation does not exist in MCDA and cannot be justified within the optimisation paradigm frequently adopted in traditional Operational Research/Management Science. MCDA is an aid to decision making in a process that seek:
    a. Integrated objective measurement with value judgment;
    b. Make explicit and manage subjectivity.
2. MCDA will not provide an objective analysis and relieve decision makers of responsibility to make difficult decisions. This is because all decisions inherent subjectivity. MCDA simply seeks to make the need for subjective judgments explicit and the process transparent.

3. MCDA will not take the pain out of decision making, but it will highlight such difficulties to help decision makers think of ways of overcoming the need for trade-offs and may prompts the creations of new options.

Therefore, based on the above, MCDA principle benefit is to facilitate or help decision makers' understanding the problem by taking into account all the parties and criteria through exploring the problem and guide decision makers to identify a decision or a preferred course of action. According to Belton and Stewart (2002), MCDA is not prescribing how decisions should be made nor describing how decisions are made in the absence of formal support.

The MCDA process is discussed next section.

3.4.1 MCDA Process

The MCDA process in practice can be grouped into three generic key phases in Figure 3-3:

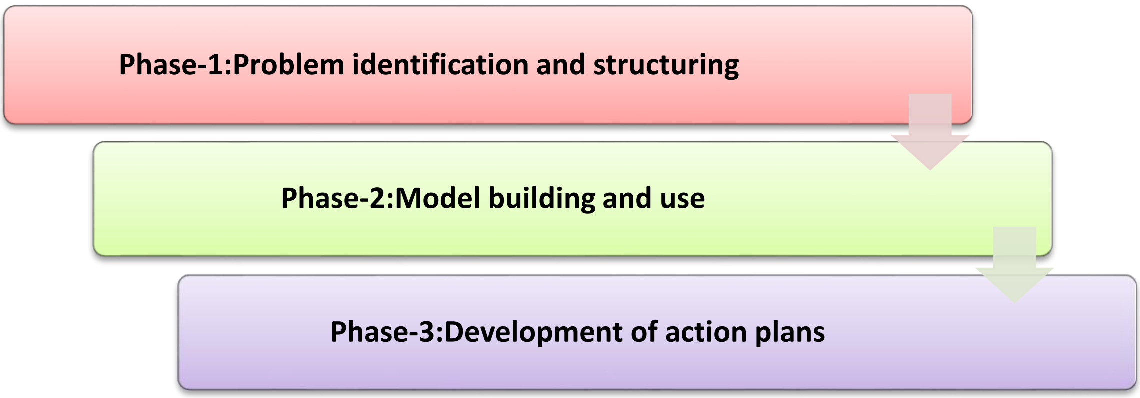

Figure 3-3: The process of MCDA (source: based on information provided in (Belton and Stewart, 2002))

- **Phase-1**: include the divergent creative thinking, opening up the aspects of the issue or options, surfacing and capturing the complexity of the problem.
- **Phase-2**: include more convergent model thinking, a process of extracting the essence of the issue from the complex representation to simplicity in a way to support more detailed and precise evaluation of potential ways of moving forward. According to Belton and Stewart (2002), here the complexity of the problem is not ignored but it emerged from it as a distillation of key factors to generate further insights and understanding.
- **Phase-3**: the plan may take many forms; for example, to implement a specific choice, to put forward a recommendation, establish a procedure for monitoring performance or maintaining a watching brief on a situation.

From the above the emphasis amongst all the MCDA process on phase-2, which is on the building and using the model, where the different MCDA methods are distinguished from each other by the following, according to Belton and Stewart (2002):

- By the nature of the model;
- The information required is elicited, specified and synthesised to inform a decision;
- How the model is used.

However, all MCDA methods have three steps in common:

- ➢ Define the alternatives to be considered;
- ➢ The criteria or objectives to guide the evaluation;
- ➢ Some measure of the relative significance of the different criteria.

3.4.2 Problem identification and structuring

According to Belton and Stewart (2002) all MCDA problems begin when someone feels that the issue matters enough to explore the potential of formal modelling. This also based on the nature of the problem and the extent to which it has been defined will have significant effect in the point of departure of analysis.

According to Belton and Stewart (2002), MCDM can be generally defined by satisfying four generic factors:

A. Some decisions to be made, which constitute in depth consideration of where the unsatisfactory area and the creative generation of possible courses of actions to address the situation.
B. Involves consideration of multiple criteria is a substantial characteristics of the problem.
C. Facilitators or analysts who attempt to guide and assist the decision maker or the person who have responsibilities for the decisions.
D. The MCDA tools or methods.

Even if the MCDM problem is identified, the MCDA categories are often based on the outcome of each type of problem in according to Belton and Stewart (2002, p15):

- ✓ **“Choice problematique:** to make a simple choice from a set of alternatives.
- ✓ **Sorting problematique:** to sort actions into classes or categories.

- ✓ **Ranking problematique:** to place actions in order preference and may not be complete.
- ✓ **Description problematique:** to describe actions and their sequences in a formalised and systematic manner for the decision maker to evaluate these actions.
- ✓ **Design problematique:** to search, identify or create new decision alternatives to meet the goals.
- ✓ **Portfolio problematique:** to select a subset of alternatives from a large set of possibilities taking into account characteristics of alternatives as well as manners in which they interact and positive and negative synergies".

It is worth noting that the above MCDM in support of MCDA problems output, they again can be further classified in according to various problem characteristics in according to Belton and Stewart (2002, p31):

- **"On-off vs. repeated problems**: decision problem need to be recur regular intervals or just a one-off decision.
- **Number of stakeholders**: problem may have single decision maker or a group of individuals or corporate executive or political decision maker acting on behalf of a large group.
- **Status and influence of client**: type of support by the analyst to client may change depending on the type of client.
- **Type of problematique**: MCDM problem listed above.
- **Range of available alternatives**: number of alternatives considered small or large (explicitly) or infinitely many or implicitly or the constraints that decision will require to satisfy and the shortlist.
- **Facilitated vs. DIY analysis**: as an MCDA can be used by any person, one person may do the analysis by himself (Do it yourself "DIY") but this case is very rare".

Therefore, in applying MCDA it is important to use the understanding of the different categories and problems to help what type of problem each different MCDA fall into and thus more MCDA methods can be more appropriate to certain type of problem than others.

3.4.3 Selecting the appropriate MCDA Method

There are many differences between the above categories. Therefore, the random utilised approaches to these different types of categories may not be appropriate. For details about these differences see (Belton and Stewart, 2002). Hence, taking into account what have been discussed in section 3.4.2 titled “Problem identification and structuring” can be of great help.

Deciding between different types of ballast water treatments (BWTS) that vary in both dimensions and dimensionless scales (e.g. Disinfection approach to eliminate the harmful organisms, risks to environment, processing time, safety, bio-efficacy, costs etc.) is a complex decision making problem. This is because all ballast water managment options have their advantages and disadvantages. Hence, a Multi-Criteria Decision Making (MCDM) method is needed for the objective of this study. According to Belton and Stewart (2002), MCDM methodologies fall into three broad categories or school of thoughts:

a) *Value measurement models*. Here the numerical scores are constructed to represent the degree of decision maker’s preferences from one alternative to another.
b) *Goal, aspiration or reference level models*. Here the desirable levels or goals are established for each criterion. Then the process seeks to discover options which are in some sense close to the desirable goals or aspirations.
c) *Outranking models*. Here the alternative courses of actions are compared pairwise in terms of each criterion, in order to define the extent to which the other can be asserted. At the end of aggregating such preferences information across all relevant criteria, the model establishes the strength of evidence favouring one alternative over another.

In addition, MCDM problems can also be generally divided into two groups (Belton, 1986):

1. *Continuous problem* is one which the solution space is continuous (infinite number of solutions) and defined by constraints.
2. *Discrete problem* involves few or many alternatives and criteria.

Therefore, the random utilise approaches/methods to these two different types of problems may not be appropriate. For example, Multiple Objective Decision Making (MODM) methods are mostly applied for the analysis of a continuous problem and may not be appropriate for the discrete type of problems (Belton and Stewart, 2002). Hence, the decision between different types of BWTS alternatives is a discrete type of problem. Therefore, in this research we are concerned about the category of a discrete type of decision problem, which normally involves limited number of alternatives and/or criteria such as the differences between BWTS alternatives.

There are many methodologies (e.g. a Simple Multi-Attribute Rating Technique (SMART); a Multi-Attribute Utility Decomposition (MAUD); Cost-benefit etc.), however, in the literature there are two commonly used MCDM approaches or methods:

- Multi-Attribute Value (or Utility) theory by Keeny and Raiffa (Raiffa and Keeney, 1976).
- Analytic Hierarchy Process (AHP) by T.L Saaty (Saaty, 1980).

There are many studies which tried to compare between these two methods from both the theoretical and the practical standpoints based on their strength and weaknesses. Nevertheless, some of the key similarities between the two common types value measurement models or methods will be highlighted, i.e. the Multi-Attribute value (or utility) theory (MAVT or MAUT) by (Raiffa and Keeney, 1976) and The Analytic Hierarchy Process (AHP) by Saaty (1980) as follows:

- Both approaches are based on evaluating alternatives in terms of an additive preference equation (3-1): $V(a) = \sum_{i=1}^{m} w_i v_i(a)$ (3-1)

  Where, $V(a)$: the overall value of alternative a; $V_i(a)$: the value score reflecting alternative a's performance on criterion i; w_i: the weight assigned to reflect the importance of criterion i.
- AHP can be viewed as an alternative means of eliciting a value function, but rests on different assumptions about the value measurement.
- As with the MAVT approach the initial steps of using the AHP are to develop a hierarchy of criteria (value tree) and identify the alternatives.
- Both MAVT and AHP model use the weight parameter (w_i) to define the levels of trade-offs between the performance on the different criteria, as the measure of performance are given by the score $v_i(a)$.
- Both methods are similar in that each weight and score is assessed by the construction of pairwise comparison matrix. Decision makers are asked to compare between the importance of two criteria or objectives in order to elicit the weights.

On the other hand, the key differences between the two are as follows:

- AHP uses the pairwise comparisons to compare alternatives with respect to each criterion and by using ratio scale (1 to 9) for all judgments. In the MAVT, an interval scale [0-100] is used to measure preferences.

- It is claimed that in AHP the weights (w_i) and scores v_i (a) are not explicitly distinguished, whereas in MAVT distinguishes between them.
- In addition, AHP uses the eigenvector approach for reconciling inconsistencies in pairwise comparisons as an ideal one because it preserves certain mathematical properties.
- AHP is often victimised by phenomenon named "Rank Reversal". Rank reversal refers to the fact when an introduction of a new alternative which does not change the outcomes on any criterion may lead to a change in the ranking of the other alternatives. However, according to Belton and Stewart (2002), rank reversal occurs because the alternative changes the scaling if they score differently for each criterion. Therefore, in AHP, the average importance of total or weights should change with addition or deletion of alternatives.
- AHP is privileged by the ability to check reliability of the judgments between pair of criteria through the inconsistency check. However, there is no formal mechanism for checking reliability between pairs of judgments or alternatives in MAVT.

On the other hand, AHP also has some disadvantages which can be revolved with its steps, transitivity, weighting the criteria and the statistical significance of the obtained results (Firouzabadi, 2005, Belton, 1986, Jing et al., 2013, Banuelas and Antony, 2004). However, discussion of strengths and weaknesses, benefits versus problems between the two widely used MCDM methods is not of a significant importance for the purpose of this study. This is because, this research presents a feasibility study for selecting the most feasible BWTS for a given ship, therefore the above differences between these two methods will not significantly influence the outcome of this research. In addition, the author believes that MCDM techniques should be used to provide or help making better decisions, giving their appropriateness to solve a particular problem.

Therefore, based on the above similarities between the two major schools of thoughts, and the ability of AHP to check reliability of judgments, hence justified our view that AHP is an appropriate method for this study which is also similar in much of its procedures and strength with some consideration to the MAVT method. Next we will highlight some of the key aspects of the AHP method application and its potential related to the problem.

3.4.4 Application of the Analytical Hierarchy Process (AHP) in the literature

The Analytical Hierarchy Process (AHP) is developed by Saaty (1980). The AHP is a highly flexible decision method that can be applied to a wide variety of situations because it is able to incorporate judgements on intangible criteria alongside tangible criteria (Saaty, 1980). The AHP use of pairwise comparisons to obtain a ratio scale of measurement is of its primary advantages. This is because it is claimed that ratio scales are a natural mean of comparison among alternatives and thus enables the measurement of both tangible and intangible factors. In addition, there are many outstanding works which have been published based on AHP including the applications of AHP in different fields such as planning, selecting a best alternative, resource allocations, resolving conflict, optimisation, etc. For example, a list of more than 145 successful applications of AHP which were divided into 10 sections for different selection problems, evaluation problems, benefit-cost analysis problems, allocations problems, planning and development problems, priority and ranking problems, decision making problems, forecasting problems, medicine and related fields problems and finally AHP was applied with quality function deployment (QFD) problems in which some were successfully published in high reputation international journals (Vaidya and Kumar, 2006). The Expert Choice software (AHP software) claimed that expert choice was used in the classroom at over 60 universities world-wide to demonstrate real-life applications of the AHP and cutting-edge decision-making and collaboration technologies (Choice, 2013). In addition, the speciality of AHP is its flexibility to be integrated with different techniques such as decision tree, Linear Programming, Quality Function Deployment, Fuzzy Logic, etc. This enables the user to extract benefits from all the combined methods, and hence, achieve the desired goal in a better way (Vaidya and Kumar, 2006). AHP methodology can also help to incorporate a group consensus (Vaidya and Kumar, 2006). Moreover, AHP allows for inconsistency in judgment, but also measures the degree to which the judgements are inconsistent and establishes an acceptable tolerance level for the degree of inconsistency (Liberatore and Nydick, 2008). AHP is a popular method because it forces decision makers to convert vague judgements to single numeric preferences in order to estimate the pairwise comparisons of all objectives and decision alternatives (Banuelas and Antony, 2004).

Evaluating and justifying between different ballast water treatment systems (BWTS) and ships that vary in their characteristics tangible and intangible criteria and conflicting between them is a big challenge of a discrete type of MCDA problem. In addition, BWTS are expected to have long life with high capital investment which is expected to be returned over several years. Selection of a BWTS is not trivial, it requires consideration of many criteria both tangible and intangible and therefore, one can see that the AHP method can provide a logical solution and can effectively be used to satisfy the aim of this study.

3.5 The developed models and AHP model procedures

3.5.1 The developed models

Based on the identified gaps from the criterial review in sections 2.3 and 2.4 respectively, various studies investigated the problem associated with the comparison and the selection between BWTS in the literature. However, there has been no study investigating the feasibility of incorporating ship related criteria/parameters in their models. Therefore, the 1st model which used the conventional Analytical Hierarchy Process (AHP) was developed as shown in Figure 3-4. The goal of the 1st model was to match the most feasible ballast water option with the most suitable ship. The two major criteria were included into two separate branches of ballast water related criteria and ship related criteria. The criteria and sub-criteria were identified based on the author's experience as well as the extensive review of relevant literature as discussed in chapter 2. However, several limitations of the 1st model were identified on the structure and the setup of the study. For example, one limitation is designed to investigate if all given ships would fit any of the given BWTS alternatives and lacked the ability to indicate which of these BWTS alternatives is the most promising for any of the given ships. Another limitation is that the model did not integrate the ship related criteria with the ballast water related criteria when matching between the most feasible alternatives.

The application of the Fuzzy Analytic Hierarchy Process (FAHP) to the 1st model was then used due to its ability to achieve better results than AHP if the uncertainties involved in real world decision problems associated with exact judgments (Chang, 1996, Bozbura and Beskese, 2007, Kulak and Kahraman, 2005). However, the results obtained by using FAHP approach for the modelled case revealed a great consistency with the results obtained by the 1st developed AHP model. Therefore, the author did not find that the application of FAHP would provide better results than using the AHP, and decided on continuing the applications of the AHP for the rest of this study. (For more details of the FAHP application study to the 1st model see Appendix E).

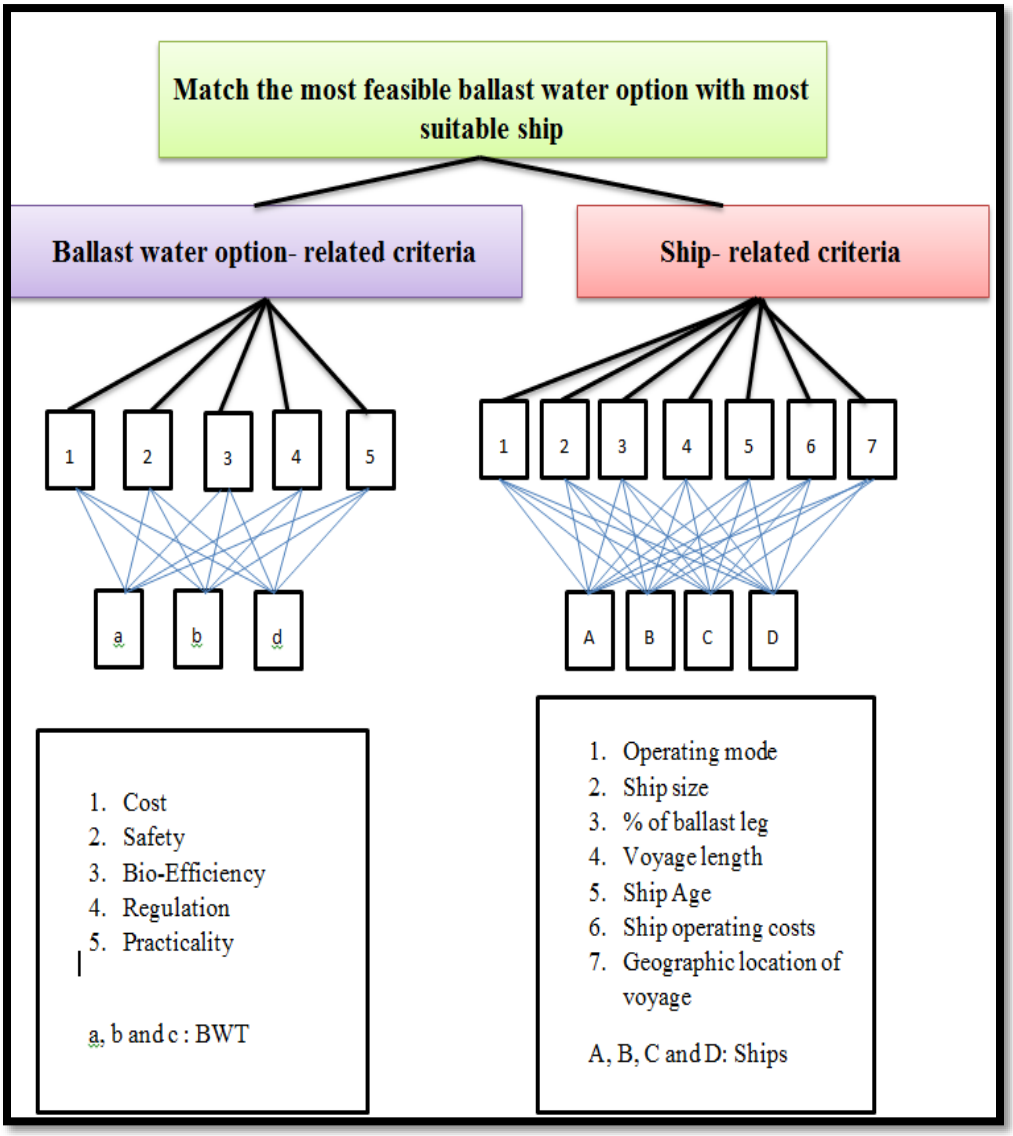

Figure 3-4: The 1st AHP model for matching the most feasible ballast water option with the most suitable ship (ALHababi et al., 2014a).

Although the 1st AHP model have some limitations, it has explicitly incorporated the ship related criteria as a separate tree imbedded into one part of the complete model structure. However, because the model was not properly structured i.e., comparing between ships in order to match with the best BWTS separately, it has indicated the importance of reconsidering the limitation in the structure by integrating both ship and BWTS identified criteria. In addition, realising a proper set up of an actual BWTS problem selection has also helped in reconsidering more criteria into this model. In response to the limitations of the 1st developed model, the 2nd AHP model is amended in which it has investigated how to select the most feasible ballast water treatment for a given ship as shown in Figure 3-5.

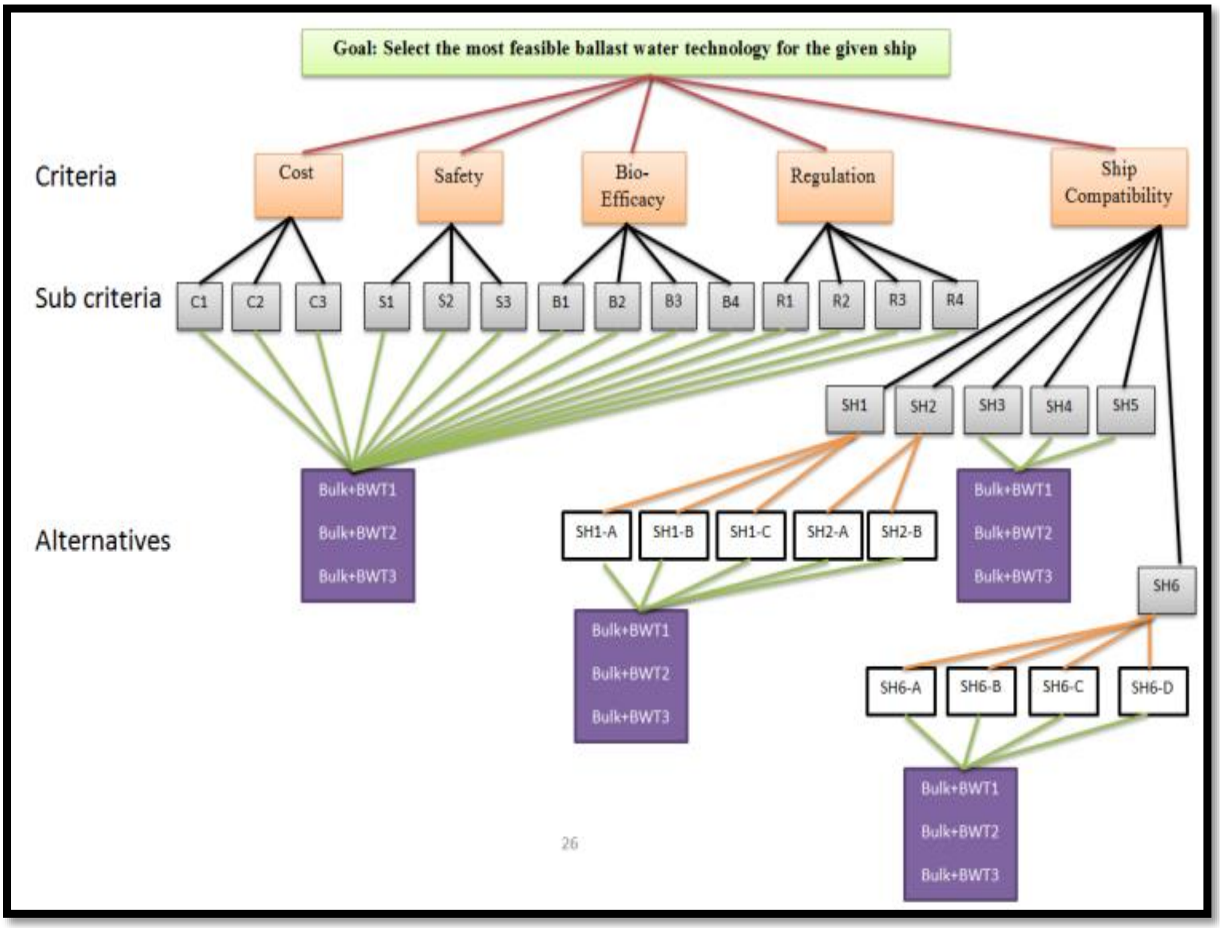

Figure 3-5: The 2nd AHP model for selecting the most feasible ballast water technology for the given ship; for more information on the model reader is advised to see (ALHababi et al., 2014b)

As shown in Figure 3-5, the goal of the model is located on the top (1st level) to select the most feasible ballast water technology for the given ship. Clearly from the model, the most feasible BWTS for the given ship is meant to be the option which obviously satisfies the identified criteria by considering both identified ballast water related criteria and ship related criteria. The global criteria are the orange boxes (2nd level), sub criteria are the grey boxes (3rd level), sub-sub criteria are white boxes (4th level) and last level are the three ship-BWTS alternatives in the purple boxes Figure 3-5. The alternative contended of a ship with an installed ballast water treatment system (BWTS) and then compared with the same ship having another type of BWTS. It is worth noting that, alternatives are not directly connected to criteria in 2nd level, but to the ones in the 3rd and lower levels. Thus, the alternatives were assessed against each sub criterion and sub-sub criterion in the AHP model. The model considered five major criteria namely: cost, safety, bio-efficacy, regulation, and ship compatibility. The cost is divided into three sub-criteria (objectives) namely: minimum capital cost (C1), minimum operating cost (C2), and minimum maintenance cost (C3). The safety is divided into three sub-criteria (objectives) namely: maximum environmental safety (S1), maximum ship safety (S2), and maximum crew safety (S3). The bio-efficacy is divided into four sub-criteria (objectives) namely: minimum effect to change of seawater temperature (B1), minimum effect to change of seawater salinity (B2), minimum effect to change of seawater chemical property (B3), and minimum effect to change of seawater clarity (B4). The regulation is divided into four sub-criteria (objectives) namely: meeting IMO regulation (R1), meeting US regulation (R2), meeting UK regulation (R3), and meeting Australia regulation (R4). The ship compatibility is divided into six sub-criteria (objectives) namely: satisfying limited space (SH1), satisfying process time (SH2), maximum ability to treat ship ballast water capacity (SH3), minimum interruption to ship emergency system (SH4), maximum ease of operation (SH5), minimum ship operating cost (SH6) (ALHababi et al., 2014b). Therefore, this model shows more promising way to select the most feasible ballast water among the given BWTS alternatives for the given ship. The study has utilised both subjective and objective information of the three ballast water characteristics obtained from extensive literature review and assumed expert's preferences. The obtained results show more robust assessment for the selection between the given alternatives by taking into consideration both ship voyage data and particulars alongside with the given BWTS alternatives.

It is worth to note that, the 2nd model required more investigation such as expert's inputs to the model, evaluating the importance of the identified criteria, and the sensitivity analysis has to be carried out in order to verify the robustness of the selected result. These gaps of the 2nd developed model are part of this research work which will be discussed in more details in the next chapters.

The next sections will discuss the steps and procedures of the developed AHP model in Figure 3-5.

3.5.2 The AHP model development procedures

The AHP process can be summarised as follow:

1. The construction of hierarchy in levels (depending on the problem complexity, identified criteria, and alternatives);
2. Obtaining priority analysis of collected data; and
3. Synthesise (combine) measures or judgments and check consistency.

The detailed procedures of the AHP calculation as follow:

1. Identify the criteria or objectives and alternatives; (can be gathered from interviews, group of experts, literature review etc.)
2. Obtain pairwise comparisons for each criterion; (can be gathered through questionnaire or engineering data etc.)
3. Normalise the resulting matrix;
4. Average the value obtained in each row to find the priority rating; (In mathematical terms, the principal eigenvector is computed, and when normalised becomes the vector of priorities).
   - According to Saaty (1980), a good method (i.e. method 3) way to normalise the mathematical matrix: divide the elements of each column by the sum of that column and then add the elements in each resulting row and divide this sum by the number of elements in the row. It is important to note that different normalising method will give different results for the general case where a matrix is not consistent. If the matrix is consistent all these differences would be the same.
5. Calculate and check the consistency ratio;
   - According to Saaty (1980), in AHP, the matrix is considered consistent if the maximum eigenvalue (λ_{max}) is closer to the number of elements in the matrix.
6. Synthesise and select the alternative with the highest score. This is done by summing the overall calculated weights of each alternative or option i.e. the overall rank of one alternative.

For more information about the steps of AHP analysis in Microsoft Excel see Appendix D.

3.5.2.1 Identification of criteria

In step 1, as in all MCDM methods call for the identification of key criteria or factors or objectives which forms the foundation of an evaluation. The ways in how these criteria are elaborated in a model structure differs between the different methodologies (or school of MCDA).

The initial sets of criteria usually emerge from the problem structuring process. In identifying these criteria, the following consideration should be taken into account Belton and Stewart (2002):

- "**Value relevance**: when the decision maker is able to link the concept to their goals and able to specify preferences which relates directly to the concept.
- **Understandability**: The decision maker should have a shared understanding of concepts to be used in the analysis in order to prevent confusion and conflict.
- **Measurability:** All MCDA implies some degree of measurement of performance of alternatives against specified criteria to specify a consistent manner. It is worth noting that different methods will require different levels of precision and different degree of explicitness.
- **Non-redundancy:** this is to prevent one or more criterion measuring the same factor. As a general rule to prevent this from happening is to combine similar criteria in a single concept.
- **Judgmental independence:** A criterion must be judged independently and do not depend on the level of other criteria. It is worth noting that the theoretical validly of a value-function approaches requires judgmental independence and violation of this condition can be quite criterial.
- **Balancing completeness and conciseness:** All the important aspects of the problem are captured and concise by keeping the level of details to minimum required.
- **Operationality:** it is important that the model is usable with reasonable effort and that the required information does not place excessive demands on decision makers.
- **Simplicity versus complexity:** the criteria set itself is a simple representation and a capturing of a problem which has been extracted from a complex problem description".

The above criteria considerations were taken into account when identifying the criteria for selecting the BWTS for a given ship. The criteria in this study were identified from the extensive literature review of relevant studies (both ship parameters and BWTS related criteria) and also by interviewing 12 experts from three different trade shipping companies to evaluate the importance and thus validating the identified criteria used in the developed AHP model.

Based on the experts experience the less important criteria were not considered in this study. It is worth noting that the definitions of all criteria were provided for experts during interviews (Appendix A).

3.5.2.2 Stakeholders

According to a website dictionary (dictionary.cambridge.org) definition, a stakeholder can be someone or group of people with an interest or concerns in a business or enterprise. Therefore stakeholders can be regulating entity as the IMO, a class society, a ballast water manufacturer, a shipping company, a port of control, a ship yard and a consultant agency. Since our focus was the development of a decision tool to assist decision makers selecting the most feasible BWTS for any given ship, shipping companies has been selected as the required stakeholder for this study.

3.5.2.3 Structure of Hierarchy

"A well-constructed hierarchy will, in most cases, be a good model of reality." (Saaty, 1980, p12). In step 1 of AHP process, the fundamental reason of building the hierarchy is to seek understanding at the highest levels from interactions of the various levels of the hierarchy. In the mathematical model of AHP for evaluating the impact of a level on an adjacent upper level is gained from the composition of the relative priorities of the criteria in that level with respect to each criterion of the adjacent level.

Key advantages of hierarchies structures according to Saaty (1980):

- Hierarchal structure of a system can be used to describe how change in priority at upper levels affects the priority of elements in lower levels.
- Hierarchal structures give great details of information on the structure and function of a system in the lower levels and provide an overview of actors and their purposes in upper levels.

No set of procedure for generating the objective, criteria, and alternatives is to be included in a hierarchy structure. However, the person who is developing the hierarchy must always be comfortable with structure and levels because they relate to the investigation experience. It is worth noting a hierarchy is not a traditional decision tree and thus it does not need to be completed and one level may represent different cut of the problem. The user of the AHP can insert or eliminate levels as necessary to sharpen the focus on one or more parts of the system.

Generally, constructing the hierarchy structure is important and helps to determine the goal of the AHP model which is normally placed in the top of the conventional AHP model

Figure 3-6. Next, the criteria (and sub-criteria) are placed at the intermediate level and alternatives at the bottom.

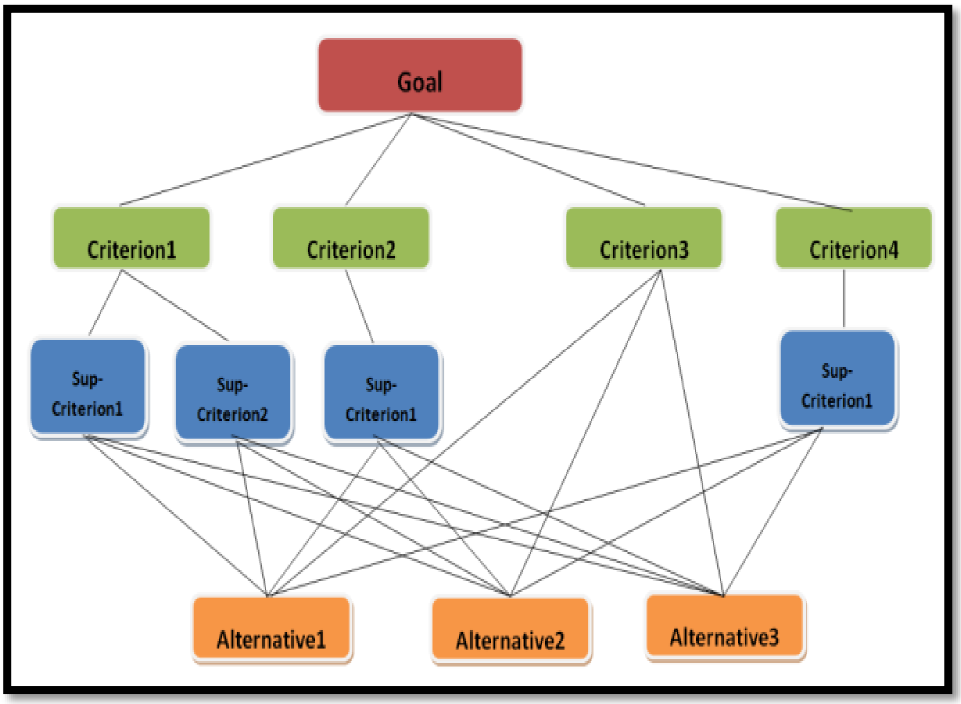

Figure 3-6: Structure of a conventional AHP model consists of a goal, criteria, sub-criteria, and alternatives from top to bottom.

The complexity of the problem normally domain the detail of the model, thus it will give an order to the number of levels in the hierarchy structure and number of criteria or factors to be considered. However, the hierarchy structure should not be complex and should be understandable for everyone. The evaluated and identified criteria or factors based on the view of the experts were used in the AHP model.

Seven typical BWTS alternatives were considered due to the limited availability of data provided by the vendors for confidentiality reasons. These factors have sharply reduced the number of the alternatives used in this research.

3.5.2.4 AHP pairwise comparisons matrix

In step 2 of AHP process, the pairwise judgment is the numerical representation to facilitate an association or relationship between each alternative and/or criterion. The criteria and sub-criteria (if exists) are used to evaluate the alternatives. It is worth noting that alternatives are assessed or judged for how good the alternatives performed under each criterion, sub-criterion, or sub-sub-criterion which depends on if the alternative is directly connected to a criterion or not. For example, in Figure 3-6, criterion 3 has been connected directly to the alternative, while criterion 1 and criterion 2 have not because they have sub-criteria, so their sub-criteria are directly connected to the alternatives. This means the criteria (or sub-criteria) are compared with another criteria (or sub-criteria) to identify how important the various criteria are to the decision because not all criteria are equally weighted by the expert or the decision maker.

In AHP the process of judgments and comparisons directly involve the decision makers (experts) inputs by allowing them to prioritise the decision criteria and sub-criteria in order to obtain the weights. Judgments and comparisons process is normally accomplished through a series of pairwise comparisons between criteria (and sub-criteria). In every comparison only two criteria or alternatives or sub-criteria are compared.

Table 3-1 shows the priority scale, 1 to 9 suggested by (Saaty, 1980) which is often used to help experts in establishing priorities of criteria or alternatives over each other. This scale is not arbitrarily chosen, but followed by continuous experimentations with large number of scales, proving the high consistency it provided (Saaty, 1980).The pairwise comparison procedure is to assign numbers to criteria or alternatives must sum to one under its parent node in the hierarchy. The 1-9 scale helps decision makers to judge the relative importance between two given criteria: how many times criterion A is more important than criterion B with concern to the overall goal? The 1-9 scale was proven by Saaty (1980) to work exceptionally well in its ability to take into account a problems with tangible and intangible information required by AHP model.

To create a pairwise comparison matrix for *n* decision element at least *n*-1 and at most *n* (*n*-1)/2 pairwise comparisons are needed to be made among the elements or criteria because:

1- By convention, elements in the matrix is equally important (*n*=1) when it compared with itself. Therefore, the diagonal of the matrix must consist of 1s.
2- There is a reciprocal relationship ($a_{AB} = \frac{1}{a_{BA}}$) between element A and element B in the matrix.

In Table 3-2, the relative contributions are expressed as a matrix of elements a_{AB} that express the strength of the contribution of “A” relative to “B” using the following scale (Saaty, 1980).

Table 3-1: Pairwise comparison scale for AHP preferences (source: adopted from Saaty (1980))

Importance	Definition	explanation
1	Equal importance	• Two activities contribute equally to objective
2	Weak or slight	
3	Moderate importance	• Experience and judgment strongly favour one activity over another
4	moderate plus	
5	Strong importance	• Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	• An activity is strongly favoured and its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	• The evidence favouring one activity over another is the highest possible order of affirmation

Table 3-2: The relative weights or preferences between two alternatives or criteria using Saaty (1980) suggested scale.

• If **A** and **B** are **equally important**, a_{AB} = **1**
• If **A** is **slightly or weakly** more important than **B** in your opinion , a_{AB} = **2**
• If **A** is **moderate important** than **B**, a_{AB} = **3**
• If **A** is **moderate plus** important than **B**, a_{AB} = **4**
• If **A** is **strongly more important** than **B**, a_{AB} = **5**
• If **A** is **strong plus more important** than **B**, a_{AB} = **6**
• If **A** is **demonstrably or very strongly more important** than **B**, a_{AB} = **7**
• If **A** is **very very strong more important** than **B**, a_{AB} = **8**
• If **A** is **extremely more important** than **B**, a_{AB} = **9**
a_{BB}; a_{AA}= 1 is **equally important** when compared with itself.

The above weights or preferences can also be derived from engineering data or expert's judgement based upon all the information and experience available to the decision maker. In AHP, the positive reciprocal matrix has the properties below:

$$a_{AA} = 1,\ a_{AB} = \frac{1}{a_{BA}} \qquad (3\text{-}2)$$

3.5.2.5 Checking the inconsistency

Judgments obtained by a pairwise comparison matrix for *n* decision element at least *n*-1 and at most *n* (*n*-1)/2 pairwise comparisons are often subjected to inconsistency as any real world problem. Therefore, as a final step, the inconsistency of the expert's judgements is possible because of the redundant comparisons. Saaty (1980) suggested Consistency Ratio (CR) equal to 10% or less to be considered acceptable. In other words, decisions made are allowed to divert from its origin with 10% or less and 90% or more are the actual accurate weighting of the provided judgments. Therefore, as a rule of thumb if CR is 10% or less, then errors are fairly accepted upper limit of CR and thus final estimates can be accepted. If the CR is greater than 10% then decision maker is required to reduce the inconsistencies by revising judgments until the CR rule is satisfied.

The consistency of comparisons is assessed by using the maximum eigenvalue (λ_{max}) after all pairwise comparisons have been completed. A consistency index (CI) is calculated with the eigenvalue. The equation used to check CR demanded for calculating the CI. CI is calculated by the equation (3-3) below (Saaty, 1980):

$$CI = \frac{(\lambda_{max} - \mathrm{n})}{(\mathrm{n}-1)} \qquad (3\text{-}3)$$

Where '*n*' represent the matrix size (number of elements) in this equation. Judgements consistency can be checked by considering the consistency ratio (CR) of the CI with the appropriate value of random consistency index (RI), as given in Table 3-3.

Table 3-3: Average random consistency index (source: adopted from Saaty (1980))

Size of matrix	3	4	5	6	7	8	9	10
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Equation (3-4) for calculating the CR (Saaty, 1980):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad (3\text{-}4)$$

For the detailed consistency check, see Appendix D.

3.5.2.6 Eigenvector method

After the matrices have been filled, the eigenvectors are calculated by the weights of the criteria and their sum is taken overall calculated eigenvector entries related to those in the next level of the hierarchy. The alternative with a higher score is defined as the most recommended alternative.

Eigenvector method has an approach to estimate the weights from a matrix of a pairwise comparison A. A must be positive and reciprocal, and filled up with the vector of weights or preferences as $W = (w_1, \dots, w_n)$ using the ratio scale and thus the weights are unique up to multiplication by a positive constant c; i.e. W is equivalent to Wc where c is greater than zero. The vector of weight W will be normalised for convenience. This method computes W as the principal right eigenvector of matrix *(*see Appendix D for more details*)*:

$$AW = \lambda_{\max} W \qquad (3\text{-}5)$$

Where λ_{max} is maximum eigenvalue of matrix A, or

$$w_i = \frac{\sum_{j=1}^{n} a_{ij} w_j}{\lambda_{\max}} \quad , for\ all\ i = 1,2, \dots n \qquad (3\text{-}6)$$

The eigenvector method has the interpretation of being a simple averaging process by which the final weights W are taken to be average of all possible ways of comparing the alternatives. In other words, eigenvector method provides an intuitive interpretation in that it is an averaging of all possible ways of thinking about a set of alternatives. Therefore, the eigenvector method is a theoretically and practically proven method for estimating the weights.

3.5.2.7 Synthesising the weights

Synthesising means aggregating the weights by adding the criteria's weight of the common nodes at the bottom level of the hierarchy to generate a composite priority vector for an alternative across all criteria as pointed Figure 3-7.

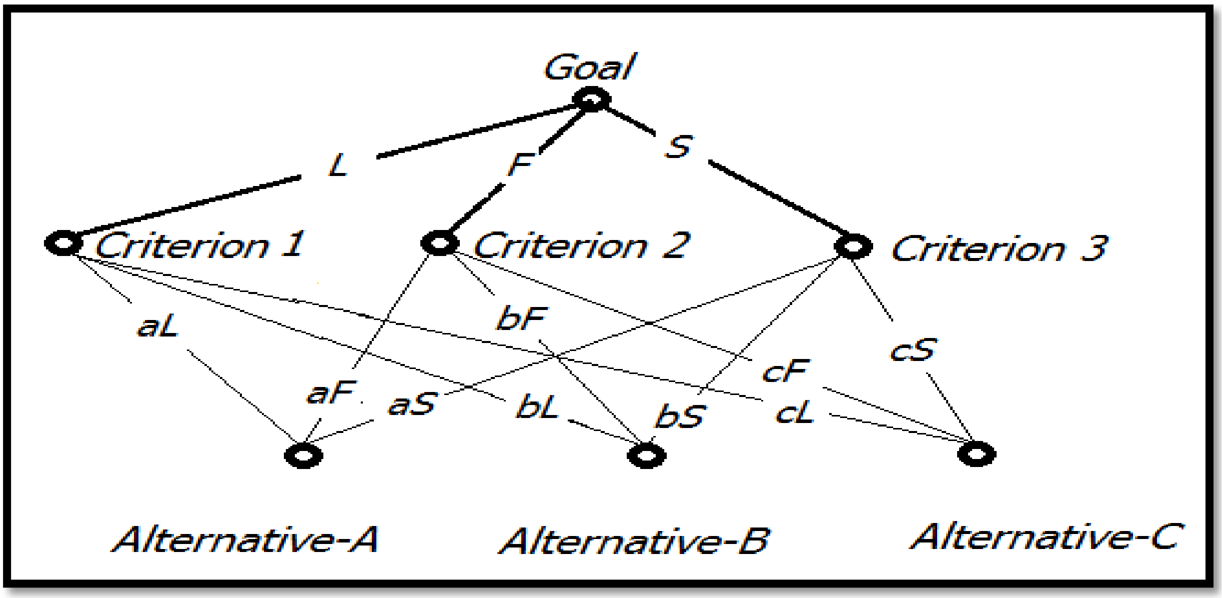

Figure 3-7: synthesising weights in an AHP hierarchy structure

Figure 3-7 shows the weights or scores of the criteria and alternatives with respect to each criterion as indicated along each line segment. In other words, according to Figure 3-7:

- The overall synthesis of Alternative A = (L aL) + (F aF) + (S aS)
- The overall synthesis of Alternative B = (L bL) + (F bF) +(S bS)
- The overall synthesis of Alternative C = (L cL) + (F cF) + (S cS)

This way, the relative weight of each alternative is assessed against each criterion and thus the relative importance of each alternative is identified.

3.5.2.8 Eliciting pairwise comparisons weights

Two ways based survey was developed using a web based survey i.e. Qualtrics online survey software (see full copy of the survey in Appendix-B) and paper based to guide experts in making comparisons (ALHababi, 2013). Therefore the results can be collected in an electronic environment or physical environment. The decision maker compares the two criteria and selects the relatively more significant one, as shown Figure 3-8.

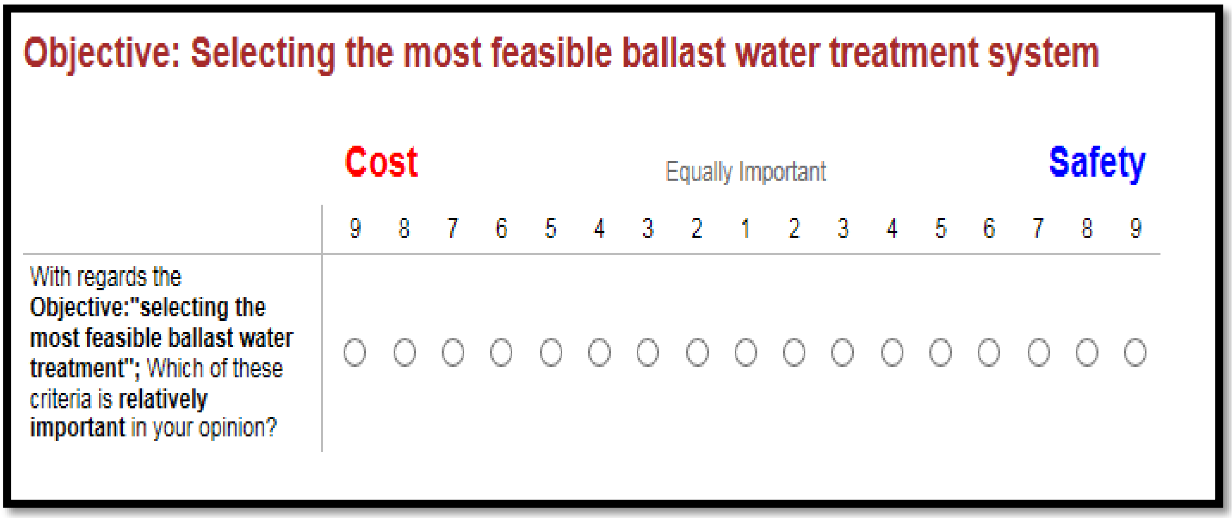

Figure 3-8: Screenshot of the prepared web-based criteria weighting questionnaires (ALHababi, 2013). The user compares the two options and selects the more significant of the two. Scale 1-9 appears at the bottom with a giving detailed description of the numerical values at the top (Source: developed by author based on questionnaire suggested in (Saaty, 1980)).

The pairwise comparison question is something like *"With regard to the objective: which of these two criteria below is more important to you?"* When the expert or user believes that there is no priority between two criteria pairs, he selects the *"equally important"* by drawing a circle around the number one (if paper based questionnaire is used) or just selecting one (on the web-based) in the given Figure 3-8. It is worth noting that the scale developed by Saaty (1980) was presented to the user with detailed descriptions of the numerical values shown in the developed questionnaire. The user was also presented with the definition of each criterion in order to avoid vague judgements. When pairwise comparisons are made by the expert, the weight of each criterion or sub criterion can be determined. For example, in Figure 3-6, assuming the weights of alternatives are (0.2, 0.5, and 0.3) respectively. These values have been derived by asking the pairwise questions such as*" which of the two alternatives is preferred or satisfies the objective or criterion 3?"*. After completing the pairwise comparisons for all the alternatives, AHP calculates the weights of each alternative with regards to that criterion or objective. These weights show that from the viewpoint of criterion 3, the best option is alternative-2. The same procedure can be applied to determine the weights of each criterion to identify how important the various criteria are to the decision. It is worth noting that pairwise comparisons are not always necessary for tangible criteria such as distance, length, and costs, unless the criterion involves a degree of utility measurement. Therefore, pairwise comparisons can be considered subjectively rather than objectively when using AHP.

Significant advantages to utilise AHP pairwise comparison through surveys offers many advantages (Firouzabadi et al., 2008):

- It allows experts to focus on the comparison between two factors or criteria or objectives or alternatives. This will allow true weights based on experience related to the problem.
- It generates meaningful information about the decision problem.
- It improves consistency in decision making process.
- The 1-9 scale has been proven to be most adequate measurement scale that enables experts to approximate the unknown weights. In addition it also works exceptionally well in its ability to take into account a problem's tangible and intangible information as required for pairwise comparisons.

In this study, the criteria weighting questionnaire was sent to one decision maker which is the head of the department and the key responsible person of the selection and installation of the BWTS.

3.5.2.9 Results from the criteria weighting questionnaire

Final results of the pairwise comparisons were obtained by taking the judgments directly from the developed web based questionnaire or survey. The preferences obtained from the decision maker (the head of the department responsible of the selection between the given BWTS) were added into the developed AHP matrix and their consistency were checked against the consistency ratios (CR) cut off point which is 10% or less. When the CR is more than 10% the expert was asked to repeat this judgments or preferences in order to satisfy the accepted CR as suggested by Saaty (1980).

3.5.2.10 Sensitivity analysis

Uncertainties of MCDA take different forms and arise from different reasons. Belton and Stewart (2002) divided uncertainties into two main categories: *internal uncertainty* and *external uncertainty*. Internal uncertainty refers to both structure of the model adopted and the judgmental requires by the model. On the other hand, external uncertainty refers to the lack of knowledge about the consequences of a particular choice. There are many differences between these types of uncertainties and thus care must be taken in order to avoid their impacts on the results obtained. Many ways could underpin such risks, for example, avoidance of imprecision or ambiguity of meaning etc.

An optimal solution is only optimal with respect to a particular mathematical decision model that provides only a rough representation of the real problem. It is in our interest to understand more than just finding the solution. The purpose of the AHP model is to help decision makers in shipping companies' final decision providing insights into the likely consequences of pursuing various managerial options under several assumptions about future conditions solution for the original version of the basic model. Most important insight is often gained while conducting analysis after finding an optimal solution for the original version of the model.

The analysis is commonly referred to as what-if analysis because it involves addressing some questions about what would happen to the optimal solution if different assumption were made about future conditions. In real world, it is seldom this straightforward. Substantial time and effort often are needed to track down the needed data. Even then, it may be possible to develop only rough estimates of the parameters of the model.

Key decision parameters (can be named criteria or objectives) for selecting one of the given BWTS for the given ship are cost, safety, regulation and ship compatibility along with their sub criteria or objectives and so on. Some of these parameters cannot be estimated with real accuracy. Therefore, before making a decision on selecting the most feasible BWTS, it will be more reasonable to understand what effect would be if one of these parameters differs significantly from the original assumption. For instance, would the optimal solution change if one or more of these parameters turned out to be different from the original assumed? How inaccurate can the estimate be in either direction before the optimal solution changes?

If the optimal solution will remain the same over a wide range of values, then the decision maker will be content with a fairly rough estimate for this parameter. On the other hand, if even a small change would change the optimal solution, then the decision maker will want to take special care to refine this estimate.

Advantages of sensitivity analysis (can be named what-if analysis):

1. Typically, many of the parameters of the AHP model are only estimates of tangible quantities (e.g. cost, temperature) and intangible parameters (e.g. safety) that cannot be determined precisely at this time. Sensitivity analysis can reveal how close each of these estimates need to be to avoid obtaining an erroneous optimal solution, and therefore pinpoint the sensitive parameters (those parameters where extra care is

needed to refine their estimates because even small changes in their values can change the optimal solution of the model) (Hillier and Hillier, 2009).

2. If conditions changes after the study has been completed (often is the case in real life), sensitivity analysis leaves signposts that indicate (without solving the model again) whether a resulting change in a parameter of the model changes the optimal solution (Hillier and Hillier, 2009).
3. When certain parameters of the model are outside the control of the decision maker. Sensitivity analysis can provides a valuable guidance regarding the impact of altering these policy measures (Hillier and Hillier, 2009).

Therefore, in this study, the sensitivity analysis is made based on the changes the relative importance of criteria and or sub-criteria in order to find out their sensitivity in changing the final decisions and thus their importance needs to be carefully considered by the decision maker.

3.5.2.11 Model validation

A model is normally validated by testing to identify whether or not it does what it is supposed to do and whether the solution offered by the model make sense. As a general approach, a model is validated by comparing the output obtained by the model with historical output data and thus validity is assessed if the output produced agreed with the test in the past, given that conditions are the same. However, in our case, there are no historical data are available and the model represents a new approach to solve a real world problem.

In addition, according to MCDA's expert said: *"There are no right or wrong answers in a MCDM models"* as explained in the MCDM (section 3.4), yet the model can be validated by defining and validating the importance of the identified criteria and indicators used. In addition, a second validation method can be obtained by evaluating the AHP model in actual case studies and working with experts in a shipping company, in our case, in order to validate the model. More details are discussed in chapter 7.

3.5.2.12 AHP Software

There is a number of very effective software packages available to support AHP:

1. Expert Choice is a well-established package making it very easy and natural to go through the entire AHP process, including building the hierarchy (www. Expertchoice.com).
2. Criterium is another well-established package making it easy and natural to go through the entire AHP process, including the hierarchy structure and building.
3. BPMSG AHP Online System is web-based software (http://bpmsg.com/academic/ahp.php), which is good but needs more inputs from the user to build the hierarchy structure, which is more difficult than Expert choice and Criterion. It is also difficult to use the sensitivity analysis using this software.
4. Decision plus was developed by Criterium Decision of InfoHarvest,Inc.USA. The software is a decision making tool that can perform the entire AHP process in making tough decisions easier to understand and to structure. However with fewer capabilities than other AHP software's.
5. HIPRE 3+ (stands for hierarchal preferences) is decision support software integrating the two most well-known easy-to-use decision analyses namely (AHP and SMART - The Simple Multiattribute Rating Technique).
6. Super Decisions is a software based on the AHP and The Analytic Network Process (ANP). The problem with this software is its difficulties for the use to build hierarchy and perform the other processes of the AHP.
7. REMBRANDT is a software which based on the geometric means rather than eigenvalues to calculate weights in AHP. It uses a logarithmic scale rather than 1-9 verbal scale used in conventional AHP, and aggregates scores by weighted products rather than by arithmetic means.

Although there are many other software programs that can be used to perform the AHP process, however; among the available packages to solve the AHP problems, the Microsoft Excel and Expert Choice were used in this thesis because:

- Readily available and user friendly;
- Accessible;
- Can be easily downloaded;
- User friendly;
- Easy to structure the criteria, sub-criteria and alternatives which also can be shown in a hierarchy structure;

- Easy to perform the necessary sensitivity analysis with graphical diagrams in Expert Choice software.

In addition, Expert Choice is a well-established decision management tool making it very easy and natural to go through the entire AHP steps, including building the hierarchy (www.Expertchoice.com). The speed, reliability and flexibility of the software to obtain results of complex decisions have increased the number of the clients and the popularity of Expert Choice applications in many governments, commercial business and academic institutions worldwide. The Expert Choice can organize, complete and communicate complex decision making tasks, which normally are tough and involve many different criteria, easier to formulate. The criteria or objectives are then compared against the various alternatives tracking the importance of those criteria and maintaining control of the overall goal is a major function of this software.

3.6 Summary

This chapter has discussed and argued the author's selected methodology and the philosophy behind the selected research paradigm adopted in this study. The overall methodology used in this study was set out, and the methods employed to collect the required type and source of data was discussed. The data analysis of the collected data, in this study, used both the qualitative approach i.e. case studies through interviews and quantitative approach i.e. developing a mathematical model. After that, the Multi-Criteria-Decision Making or Analysis (MCDM or MCDA) were introduced. The similarities between two popular MCDA methods under the value measurement models are named the Multi-Attribute value (or utility) theory (MAVT or MAUT) by Keeney and Raiffa (1976) and the Analytic Hierarchy Process (AHP) by Saaty (1980). Both approaches are based on evaluating alternatives in terms of an additive preference function view and other similarity. It was argued and justified that AHP is similar with some consideration to MAVT in much of their procedure and strength as MCDM, and the AHP can check the reliability of the judgments, therefore it has been used in this study. In addition, exploration of the wide range of the successful AHP application in the literature has proven that AHP is an appropriate method that can be used for developing a decision tool to support decision maker to select the most feasible BWTS for their ships. Finally, the theoretical and procedural process of the application of the AHP method used in this study along with the detailed explanation of each specific step is discussed.

It is worth noting that, the originality of this research is not from the methodological context because there are no changes performed to the conventional AHP method, but from the application context by using the MCDM i.e. AHP to develop a new model and solve a real world ballast water treatment system selection problem under different criteria and considerations.

Chapter 4 will provide an overview of the case study of interviews with 12 experts.

Chapter 4: Case Study-Experts Interview

4.0 Introduction

This chapter provides a detailed overview of the interviews which were conducted with twelve experts from three leading different trade shipping companies in a case study. The shipping companies were introduced firstly. Secondly, the interviews and interview analysis are discussed in the next sections of this chapter. Finally, the summary and the conclusions which were learned from the interviews are presented at the end of this chapter.

4.1 Shipping Companies

4.1.1 Oil Tanker Company (OTC)

OTC was founded approximately sixty years ago by a group of pioneer investors, who had a vision on the importance of the growing sea borne transportation and the development of the oil industry after the great discovery of many parts around the world. OTC is partnered by forty nine percent shares with the government, thereby boosting its development.

The persisting increase in the world demands for oil as a major source of energy created the importance of its transportation activities in the crude oil, refined and liquefied products to the ultimate consumer.

In 1959, OTC took delivery of the first crude oil tanker "*KAZIMAH*" 49,000 Metric Tons. By 1975 the fleet had been expanded to transport over one million metric ton (MMT) of crude oil, but due to the expansion of refinery capacity in Middle East, product tankers were also acquired along with liquefied petroleum gas (LPG) carriers. In 2001, the OTC fleet reached 25 ships of different sizes and purposes which had deadweight capacity of 3.2 MMT. In 1993, the OTC fleet reached its maximum number of ships totalled of 38 ships with capacity of 4.1 million Metric Tons. Today, OTC owns a fleet of 31 ships, with different ages, which can transport approximate total capacity of 18.6 MMT. In 2014, the OTC admitted three VLCCs and four product carriers.

Changes of the fleet number of ships is a normal strategy followed by the OTC with the general slackness conditions in the tankers industry all over the world during the current years, in order to keep its profitability above the regular average due to its intensive concern for reducing the operating expenses and its wise policy of replacing old ships at the appropriate times.

The OTC is mainly involved in the ownership and management of tankers engaged in the transport of crude oil, refined petroleum products and liquefied petroleum gases (LPG). In addition, OTC also acts as a Marine Agency Branch and the sole agent of all tankers calling at the sea ports and Gas Branch for filling and distributing LPG cylinders for local industry and domestic consumption. In line with the company's mission and strategy to maintain a high standard fleet to cater for company's requirements, the Fleet New Building Projects Group (FNBPG) handles all issues pertaining to fleet renewal projects. Whilst, the responsibility of handling all issues pertaining to OTC fleet and making decision for selecting a ballast water technology fall under two separate departments namely the Fleet Engineering Group (FEG) and the Fleet New Building Projects Group (FNBPG). This means that the FEG is responsible for all the existing ships while the FNBPG is responsible of the new building ships. Decisions on the selection of a ballast water treatment system are normally made by each department's decision maker and that is normally the head of the department.

4.1.2 Livestock Company (LC)

LC is a public shareholding company established in 1973. It is considered one of the pioneering international companies in livestock transport. LC had a fleet of four livestock carriers' ships transporting its main cargo between Australia and the Arabian Gulf region. Today the LC comprises a fleet of 34 and 29 years old converted livestock carriers. Today, LC is planning for delivering the third livestock carrier after dismantling one of their old carriers which is still under construction at the ship yard.

The responsibility of handling all issues pertaining to LC fleet and making decision for selecting a ballast water technology fall under the Marine Fleet Department (MFD). The MFD have a fleet manager and two superintendents i.e. engineer and operational. Decisions on the selection of a ballast water technology are made by the head of MFD.

4.1.3 Bulk Carrier Company (BCC)

BCC was founded approximately fifty-five years ago by a mid-sized family-owned business, which started as a single ship owner in 1960. This step was the beginning of a long story of success which is still moving ahead at full speed today. There are many factors sustaining the company's success, not the least of which include the steady growth of the company's own fleet and the continual expansion of its business operations.

Today, BCC fleet comprises of 47 ships distributed between owned and operated with ship’s age between six and seven years old. BCC is a main trader in the region of the Mediterranean Sea, North Sea, Red Sea and Baltic Sea. BCC cargo traded consists of material which are used for building and road constructions, fertilizers, steel, and agriculture.

Services provided by BCC are listed below:

- Purchase and construction of ships (new and second-hand projects)
- Technical and marine inspection (ship visits and coordination)
- Supervision of dry-docking
- Repairs and refitting
- Maintenance and reconditioning of ship's engines by in-house personnel
- Procurement and warehousing of spare parts
- Shipping of spare parts and stores including customs and shipping documents.
- Marine insurance
- Loss adjusting and claims management
- Security and quality management to international standards
- Cost planning, cost control and budgeting
- Technical and financial inspection of the on-board inventory
- Acceptance of new ships and commissioning of new ships for our own and third-party fleets
- Crewing, in close collaboration with a crewing agency
- Developing database-supported materials management systems for improving operational efficiency on board and on land

The technical department of BCC is the responsible department for making decisions on the selection of ballast water treatment system for the company’s fleet.

4.2 Sampling

"*A sample is a subset of a population and should represent the main interest of the study*." (Collis and Hussey, 2003). Since the focus was the development of a decision tool to assist decision makers selecting the most feasible BWTS for their ships, shipping companies has been selected as the required population for this study. To be realistic in the practice, we cannot interview all shipping companies due to time and money constrains and thus a sample of three representative shipping companies was required. Therefore, three different trade interests shipping companies were chosen for this study. These companies were selected because they are considered leading shipping companies, able to be interviewed in English; kind agreement to make data available; responded to the invitation emails and arranged meetings date and time to facilitate the interviews. In addition, the paradigm adopted here is a qualitative approach one and thus it required depth rather than width. These interviews were conducted in the period from July to August 2014.

4.3 Interviews

4.3.1 Introduction

Interviews were arranged by making phone calls and sending emails to the responsible senior staff personnel and managers. In this study, these senior staff and managers are considered experts. Before the interviews, initial emails and phone calls were conducted to identify these experts in each company. A brief introduction of this PhD study about the ballast water treatment systems (BWTS), and the current challenge of selecting the most feasible BWTS for any given ship were introduced. The objective of the interviews was to acquire more in-depth understanding of the shipping companies' views with regards to the challenge of selecting between the different types of BWTS for their ships and aggregate the criteria that should be considered when selecting between the given alternatives for their ships.

Therefore, these interviews and discussions were conducted with the appropriate respondents, those who hold on authority or knowledge to make decisions on the selection between BWTS in these three different trade interest shipping companies.

The expert interview questions are divided into five sections. Section A consists of introductory questions; Section B consists of ballast water treatment systems questions; Section C consists of the parameters considered for comparing between ballast water treatment systems questions; Section D consists of added ship related parameters questions; section E consists of close questions. This is attached in Appendix-A.

The interviewed experts were conducted with a Ship-Owner and a Fleet Manager; The Manager of the Fleet Department, Engineer Superintendent, The Marine Operation Superintendent, The Superintendent Fleet Projects Manager, Fleet New Building Projects Group Manager, The Fleet Engineering Group Manager, The Manager Fleet Engineering Group, Superintendent Engineer Senior Specialist of the Fleet Engineering Group, and Team Leaders Fleet Engineering Group.

From the above, the interviews were conducted with the key responsible personnel or experts from the three different trade shipping companies in order to seek in-depth the understanding of the topic under investigation.

4.3.2 Analysis of the interviews

The interpretive approach was used in order to analyse and identify all the aspects that were found and discovered during the semi-structured interviews in English with experts from the three different trade shipping companies. The output learned from the interviews is presented in the following sections.

All the interviews were conducted at the company's head office; expect one interview which was conducted at a conference in a quiet area. The interviewer was welcomed in a very professional and friendly environment. All the interviews began immediately after arriving the office in order to prevent interruption the busy time of the experts. The interviewer reassured the experts that their names, companies and any response will be kept confidential and that their answers will be used for the purpose of this PhD research only.

Before proceeding to the question sections of each interview, the interviewer provided the respondents the first page of the expert interview sheet, and explained the aim of this interview stressing on the purpose of the interview as part of the PhD study on designing a decision tool to assist shipping companies to select the most feasible ballast water treatment system for their ships.

The challenge of selecting between the various ballast water treatment systems (BWTS) which claimed to effectively meet the International Convention for the Control and Management of Ships Ballast Water and Sediments (BWM Convention) which was adopted by the International Maritime Organization (IMO) in 2004 was also discussed for its importance as a solution and an existing challenge.

The differences between different BWTS (e.g. risk, cost, processing time, capacity etc.) are briefly discussed and then followed by the bold question which is clearly stated in the first page: **Which of these BWTS should a shipping company install into their ships?**

All the interviewees were in an agreement that the selection between the different BWTS is very important issue in the current marine industry. It is one of their primary concerns particularly the BWM Convention is coming soon into force. Additionally, the sound of designing a decision tool was a welcomed idea particularly when there was so many things to think about when it comes to making big decisions and no chance for mistakes.

The manager of the Fleet Department sounded very excited of the topic and said: *"You've just came in the right time, because we were in the process of searching the market in order to select the best BWTS for our ships, especially that we have just dismantled one of our old ships, and we are constructing a new ship at the moment, and thus selecting the best BWTS is one of our issues that we need to make a decision on".*

The Superintendent Engineer and Senior Specialist said: *"I am glad to hear that there is an effort in developing a decision tool to assist selecting between the given BWTS as this topic had many internal meetings with higher ranked managers aiming to set out a clear short list of rules that need to be considered by our company when making decisions on any ballast water treatment system which I personally do not agree with some of it nevertheless have to follow the rules".*

Therefore, aggregating aspects and opinions about the criteria that should be taken into account when selecting a ballast water treatment system were thought very important and interesting from the point view of the interviewees.

4.3.2.1 Section A: Introductory Questions

Please note that some of the reported answers from the introductory section were used to explain each shipping company in the previous section of this chapter. Before starting the section of the introductory questions, the interviewer explain the aim of the introductory section which is to gain as much details as needed of the shipping company. In addition, the interviewees were informed that the questions are going to be open type of questions and thus notes will be taking during the interview. All the interviewees agreed for the notes to be taken and this has also prepared the interviewees to answer the interview questions.

In the **first question** the interviewees were asked to describe their company and its main activities.

The interviewer had to give more explanations to this question as if it was too long and confusing because it has two separate parts of questions in one. For example, first one should had been about describing the company structure i.e. the number of departments, and the second question should had been about explaining the company main activities i.e. what they really do.

As a result, some of the interviewees jumped into answering this question immediately by describing their company activities and services that they provide only. However, the interviewer had to remind them about the second part which is on the structure of the company.

In the **second question** the interviewees were asked how many ships does their company operate/ own and if possible provide their size in deadweight tonnes and age.

A difficulty was noted in answering this question, and that could be due to the different number of ships that each shipping company have. For example, two interviewees from the same shipping company but different departments provide different numbers of the ships that their company owns. Therefore, they advised the interviewer to check the website for more details. On the other hand, in the small size shipping company the interviewees were able to give the names of the ships, the year of build and the size of their ships without any difficulties.

In the **third question** the interviewees were asked about the type of cargo carried by their ships.

All interviewees jumped into answering this question immediately by listing what type of cargo transported by their ships. The OTC respondents answered together that their cargo's varied from crude oil, products such as (gas oil, diesel oil, Jet fuel, heavy fuel oil) and liquefied petroleum gas (LPG) such as propane and butane gas. The Livestock shipping company explain that the major cargos are livestock such as sheep, horses and cows and other minorities with the sheep as their major trade. The bulk carrier shipping company respondent explained that main cargo traded consists of materials which are used for building and road constructions, fertilizers, steel and agriculture.

In the **fourth question** the interviewees were asked about the destinations that their ship sails to (geographic trading area).

The OTC interviewees explained that their ships sail worldwide with their major unloading areas are Japan, Korea, Taiwan, Indonesia, Pakistan, and India, and their major loading area are Kuwait, Saudi Arabia, United Arab Emirates UAE and West Africa.

The LC interviewees explained that the major loading area is Australia and their major unloading area is the Arabian Gulf.

The BCC interviewee explained that their trading areas are Norway, Egypt, Baltic Sea and the North Sea region.

In the **fifth question** the interviewees were asked to give approximation of the annual volumes of cargo transported (ports of loading /unloading).

Difficulties were noted in answering this question, some respondents replied that they can't provide the interviewer with more precise information and suggested to provide the interviewer with printed documents. Nevertheless, they provided their approximations as follow:

The Oil Tankers Company's interviewees provided an approximation from 2.4 million barrels to 18.6 million tonnes.

The Livestock Company interviewees provided approximations from 75,000 to 80,000 heads in about 8 to 9 trips.

The Bulk Carrier Company interviewee provided approximations of 3 million tonnes of annual cargo carried by their ships.

Based on the above information, it can be understood that all these shipping companies are leading companies each in their trade of interest.

4.3.2.2 Section B: Ballast Water Treatment System

In the **first question** the interviewees were asked to give their opinion from the environmental perspective, how important is it to implement a ballast water treatment system and meeting the IMO BWM Convention.

All interviewees had different views i.e. some were positive and other were negative with regards to the importance of installing BWTS to prevent the documented threats of the bio-invasion phenomenon which were documented in the literature to be caused by ship's ballast water as a key vector. For example, an interviewee said: *"Our ships are about 5000 m^3 ballast water capacity and thus we will certainly have to comply with IMO regulations when it enters into force; however, I can guarantee you that our ships are not causing any species translocation threats. This is simply because we are short shipping so we really do not need to install ballast water treatment systems".*

This opinion was similar to the other interviewee who said: *"From environmental perspective this regulation is just exaggerating the problem for someone to benefit, ships and the ballast water contamination or species show no such high risks, especially if we just look at the temperature change between two regions and to my understanding this is enough to limit the spread of species. In addition, the largest ballast water capacity tanks in our ships are permanently filled with freshwater from ports for breeding purposes, yet we indeed have to comply with the international regulation when ballast water convention enters into force."*

However, another interviewee said: *"I believe that ballast water management convention is a positive step; we cannot fake the truth that ships are responsible for such an issue. One of my personal hobbies was diving, and I have witnessed the changes of our beautiful reef over 30 years. We cannot ignore the fact that some ships do not follow the regulations, but others do. Therefore, managing the ballast water through technologies will hopefully eliminate this problem".*

Therefore, although all shipping companies seemed to have disputes within their opinions about the importance of implementing a ballast water treatment system (BWTS) because some have considered themselves contributors to issue of bio-invasions and species translocations while others did not. Nevertheless, they've all responded positively about the importance of the compliance with the IMO BWM Convention when it enters into force by implementing a suitable BWTS on-board their ships.

In the **second question** the interviewees were asked about their company future plan for meeting the IMO BWM Convention when it enters into force (e.g. using chemical inactivation; physical inactivation; ballast free ships?)

Difficulty in understanding this question was noted in all interviews. The interviewer had to add more explanations of what really needed to be known. One interviewee said: *"IMO BWM Convention and regulations has to be complied with, therefore we are conducting market research on the BWTS, and we are currently waiting for a quotation from one BWTS vendor".*

Another interviewee said: *"We are planning to install Ultraviolet (UV) from a particular ballast water vendor into all our ships, and avoid any chemical treatments. Any vendor with chemical treatment comes to our office had been and will be sent away with no chance for negotiations. We just can't bear any risks to ballast tanks corrosions and ship structure integrity at all".*

Another interviewee said*: "based on huge research we've just recently conducted. The usage of active substances ballast water treatment system such as chemical treatments will affect the ballast water tank's coating and increase the corrosions, therefore to lower such a risk; ballast water systems with no active substances are more prioritised such as Ultraviolet".*

Therefore, it is clear that shipping companies do vary in their depth of understanding about the different BWTS; however there is a clear rejection to any chemical ballast water treatment system and the key reason is based on wonders if it will really affect the ballast water tanks' coating and increase corrosions.

In the **third question** the interviewees were asked about how much information have they obtained about the BWTS?

Some interviewees answered this question briefly by listing the sources of information that they are using to obtain an understanding of how a typical BWTS works such as: technical information from the ballast water vendors' websites which some also provide video explanation of how the system works, copy of their IMO type approval certificate, their international offices to contact, and class society approval.

From this question, it was understood that shipping companies do not use information's from conferences or academic journals in order to understand the differences of the different

BWTS as expected. They always go to big exhibitions to see what products are available and ask for the information to be sent to them.

In the **fourth question** the interviewees were asked if their shipping company have any concerns about these BWTS.

All interviewees had different views depending on their research. For example one interviewee said*: "no we have no concerns because all BWTS are approved by IMO"*. On the other hand, another interviewee said: *"A ballast water treatment system that uses active substance may affect the ballast tanks' coating and they require extra treatment before discharging the ballast water, consume more power which is why it should be avoided".*

In the **fifth question** the interviewees were asked about the current BWTS already installed or intended to be installed on-board their ships?

All interviewees answered this question positive without any doubts that Ultraviolet (UV) and filtrations is the intended or already installed in their ship's ballast water treatment system. One interviewee said that their company have already installed UV ballast water treatment system on-board nine of their ships.

It was also noted from the interviews that most of shipping companies are currently performing ballast water exchange (D-1 standard) and using the ballast water record waiting for BWM Convention to enter into force before they decide to seriously implement any BWTS in order to meet D-2 standard. Probably this behaviour of not taking this Convention seriously is the prolonged delay of the BWM Convention which was supposed to inter into force 12 months after the date on which is not less than thirty countries with not less than 35% gross tonnage of the combined fleets of the world's merchant shipping. Yet this Convention has not entered into force due to many challenges, as in 30th September 2014 (time of writing this report), 40 countries have ratified to the convention however with combined fleets of 30 % gross tonnage (http://www.imo.org).

In the **sixth question** the interviewees were asked if their shipping company compares between the available BWTS for selecting one.

Misunderstanding this question was noted. The answer which was expected to be on the form is '*Yes or No'* only, however, some interviewees continued listing criteria and the interviewer was not able to stop them as all their answers were of highly valued answers. This has forced the interviewer to skip repeated questions.

For example one interviewee said*: "No, we are currently just negotiating and receiving quotations from some ballast water treatment's vendors. But definitely will carry out such task before making any decision*".

On the other hand, all interviewees answered this question confidently, *"Yes"* and started listing criteria and factors that they've taken into account when comparing between the BWTS. The key criteria or indicators noted for comparing between BWTS are: *" capital cost; installing cost; reputation of the vendor; colleague's opinion from other shipping companies; piping requirement and cost; extra pump requirement; power requirement; length of voyage compatibility; maintenance cost; operating cost; BWTS footprint; process time; hazard free; spare parts availability; good service offered by BWTS vendor; simplicity of operation and maintenance; approved by recognised classification society and administration; accepted by United States Coast Gourd (USCG); presence of BWTS vendor in regions (e.g. Middle East, Far East, Singapore, Europe and USA); BWTS have already installed into at least three existing ships; BWTS obtained type approval certificate; BWTS must match ship ballast pump capacities; the ballast water vendor warranties; and reliability"*.

In the **seventh question** the interviewees were asked to define the department which is responsible for comparing between the different BWTS?

All interviewees had different number of departments depending on the size of the shipping company. For example, one interviewee said*: "The fleet department is responsible for all the matters regarding our ships such as, the maintenance and repairs, building, ship operations, purchasing equipment, and the selection of any part into our ships such as installing a ballast water treatment system".*

Another interviewee from another shipping company said*: "In our company, the technical department is responsible for comparing and selecting a BWTS".*

On the other hand, an interviewee said: *"In our company there are two separate departments, one is responsible for the new build, and the second one is responsible for the existing ships. The decision for selecting a ballast water treatment system comes from the responsible department whether it's for new built or for an existing ship."*

From the above, it is understood that the decision on the selection of a particular ballast water treatment system is normally made by one decision maker.

In the **eighth question** the interviewees were asked on the number of departments normally involved in making the decision of selecting BWTS?

This question was answered by the interviewees above.

In the **ninth question** the interviewees were asked about the procedures that were needed to be made when selecting the BWTS?

This question was answered in question 6 above. A difference between the procedures followed by the shipping company was noted in this question. However, there is no specific procedure-order followed by a shipping company was noted from the interviewees. For example, one interviewee said: *"We've looked at the capital cost, the installation cost, the reputation of the ballast water treatment vendor, the quality of service provided such as warranties, colleagues opinions, and the reports provided".* Another interviewee said*:" we've considered the space, the required piping work, the position and the location, the capacity of the BWTS, and then the time compatibility check for our ships".*

Another interviewee said: *"We've selected the UV ballast water treatment after comparing the footprint, capacity, trade pattern and length of voyage, the installing cost, capital cost and operating cost with other given alternatives".*

One other interviewee said: *"We've looked at the criteria of all aspects such as power requirement versus the power availability; ballast water treatment vendor reputation; any requirement of additional equipment, warranties, owner benefit, location in the ship, hazard free, service network for spare parts, service quality, good service, and risks".*

Another interviewee emailed the interviewer on 10th August 2014 with the following procedures followed by their shipping company based on higher management instructions summarised below:

- *"1st no chemical or residual chemicals and /or effluents to be implemented into our ships";*
- *"The size, power consumption, simplicity of operation/maintenance and overall operational cost to be considered";*
- *"Approved by recognised classification society; accepted by US coast guard";*
- *"Existing type approval certificate; already installed on minimum three ships";*

- *"Sufficient global presence in strategic locations"*

Procedures of evaluating and selecting BWTS, according to their company are summarised below:

- *"Review drawings*
- *Review makers details based on criteria of the shipping company*
- *Study the existing ballast water system on board and assess the locations where the ballast water treatment can be fitted.*
- *Physical check on-board*
- *Modify schematic ballast system drawings for short listed makers*
- *Assess pressure loss*
- *Assess suitability of existing ballast pumps*
- *Assess impact of electrical load on generators capacity of the ship*
- *Assess additional work in terms of steel, piping, valves, and electrical instrumentation".*

From the above, it was very interesting that shipping companies were aware of the many and complicated criteria to look for when comparing between given BWTS alternatives. Yet, their answer shows that there are no particular procedures or steps taken when selecting a ballast water treatment system. It was also noted that criteria were considered procedures to some interviewees.

In the **tenth question** the interviewees were asked if their company use any model, tool or software to assist selecting BWTS.

All the interviewees submitted the answer *"No to having a model or tool to assist in selecting BWTS".* However, one interviewee said that their company uses a third party such as a class society to do this job on behalf of the shipping company.

In the **eleventh question** the interviewees were asked if they would find it useful to have a decision making tool to help their shipping company selecting the most feasible BWTS for each ship?

All interviewees said: *"Yes, it will be very useful to have a decision making tool to select the most feasible BWTS"*. One interviewee said: *"If such a tool is proven to be reliable, then indeed yes it will be very useful".* However, one interviewee did not have the same interest and said: *"No not needed".*

Therefore, it was noted that although shipping companies do have enough knowledge about the parameters to compare and select BWTS, however they do not have a model or a tool to assist them selecting the most feasible BWTS for their ships. In addition, not all shipping companies think that such a tool is required; however, the majority did find it useful to use.

In the **twelfth question** the interviewees were asked to give reasons for their opinion given in question number 11?

All interviewees who answered *"Yes"* to question 11 provided the following reasons: *"Because it will save time and money, lower efforts on research, reduce human error, and can take many parameters and complexities of such decision away from the decision maker"*. On the other hand, the only one interviewee who remarked that such a tool is not required said: *"Because all of our ships are the same sizes and types which called sister ships with similar trade pattern"*.

From the above, it is noted that small shipping companies may or may not find such a tool useful depending on the number of ships, size and trade pattern that their ships sails through. On the other hand, all the interviewees agreed on the importance of developing such a tool.

4.3.2.3 Section C: The parameters considered for comparing between ballast water treatment systems for a given ship

In the **first question** the interviewees were asked in case that their company uses a specific tool or model, which parameters are used for the comparisons between the ballast water treatments systems?

This question was answered by all interviewees in the previous section and thus the interviewer asked if they can add more thoughts of parameters that should be considered when selecting a BWTS.

One interviewee added the following: *"Pressure differential; maintenance required; cost; spare parts availability; training crew; compatibility; simple and easy to operate; vendor reputation are most important to me".*

Another interviewee said*: "Cost of the BWTS; operating cost; suitability to be fit in our ship, flow rate and pressure, pump capacity; type approval certificate; reliability; vendor* *reputation; simplicity of operating BWTS; availability of spare parts are enough to compare between BWTS".*

Another interviewee said*: "No chemical or by-products and any environmental aspect; space; cost; position; timing for treatment".*

Therefore, the interviewees have indicated by repeating the criteria which are, the capital cost and operating cost, ship compatibility (suitability), maintenance, vendor reputation, crew training, spare parts availability; space and position of the BWTS. Some interviewees stressed on no chemical or by-product to be used for ballast water treatment is allowed on-board their ships.

In the **second question** the interviewees were asked in case that their company do not have a specific tool, then which parameters they suggest be used for the comparisons between the BWTS?

This question was thought to be just a repeat to the one above and thus had to have the same answers as above.

In the **third question** the interviewees were shown a table that listed the identified criteria and indicators which were acquired from the literature review and used by the AHP decision tool which was presented in (ALHababi et al., 2014b) Table 4-1 (see Appendix A for more details).

The interviewees were then asked to rank the importance of each indicator from 1 to 9, and the highest rank '9' represents the most important criteria and indicator. The definitions of the criteria and indicators were presented to the interviewees before ranking any criteria in order to prevent misunderstanding of the meanings of any criterion or indicator (definitions are provided with the interview sheet in Appendix A).

Table 4-1: ballast water treatment systems criteria and indicators

Identified criteria	Indicators
1. Cost	• Minimum capital cost • Minimum operating cost • Minimum maintenance cost
2. Safety	• Maximum environmental safety • Maximum ship safety • Maximum crew safety
3. Bio-efficacy	• Minimum effect to change of seawater temperature • Minimum effect to change of seawater salinity • Minimum effect to change of seawater chemistry • Minimum effect to change of seawater clarity
4. Regulation	• Meeting IMO standards • Meeting other states standards
5. Ship compatibility	• Satisfy limited space • Satisfying process time • Maximum ability to treat ship ballast water capacity • Minimum interruption to ship emergency system • Maximum ease of operation • Minimum ship operating cost

It is worth noting that interviewees recommended that Bio-efficacy to be combined into the Regulation as one single criterion as they both serve the same purpose. Based on that, the interviewer asked the interviewees to evaluate only one criterion in order to define its importance. The outcome evaluations of the above criteria are as follow:

- The safety and the regulation criteria scored the highest (9 out of 9), followed by the ship compatibility (8 out of 9); and finally the cost at (7.75 out of 9) Figure 4-1.

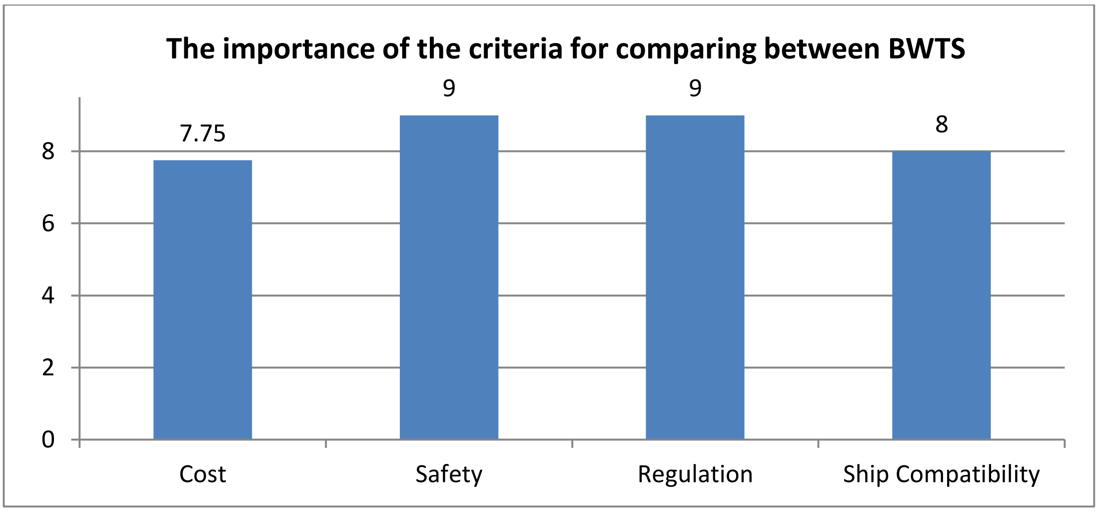

Figure 4-1: The importance of the criteria for comparing between BWTS

- All of the cost indicators are considered important i.e. the minimum capital cost indicator scored the highest (8 out of 9), followed by the minimum operating cost (7 out of 9) and finally minimum maintenance cost at (6.25 out of 9) Figure 4-2.

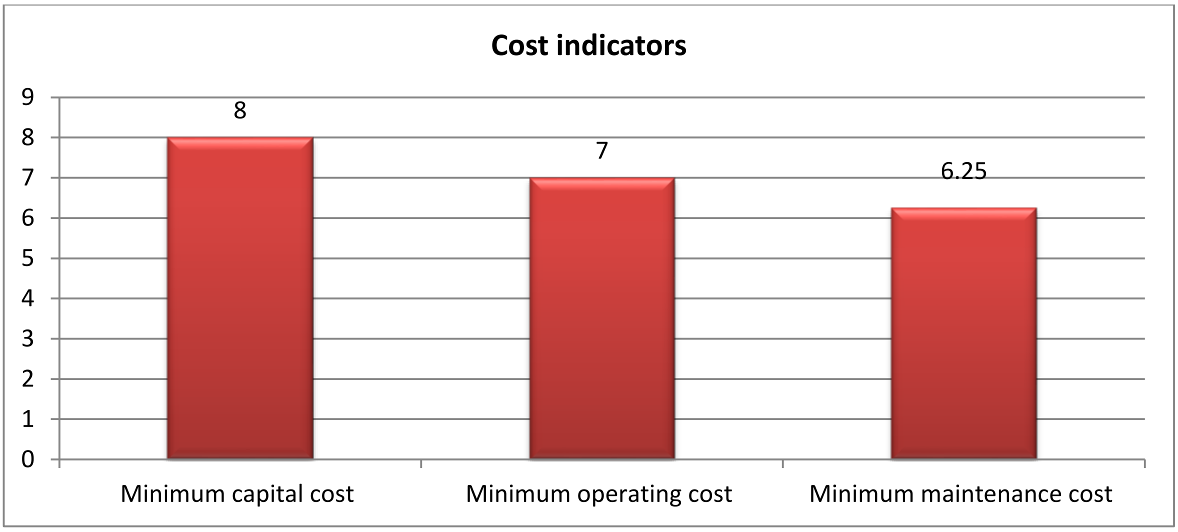

Figure 4-2: The average importance of the cost indicators

- All of the safety indicators are considered extremely important (9 out of 9) Figure 4-3.

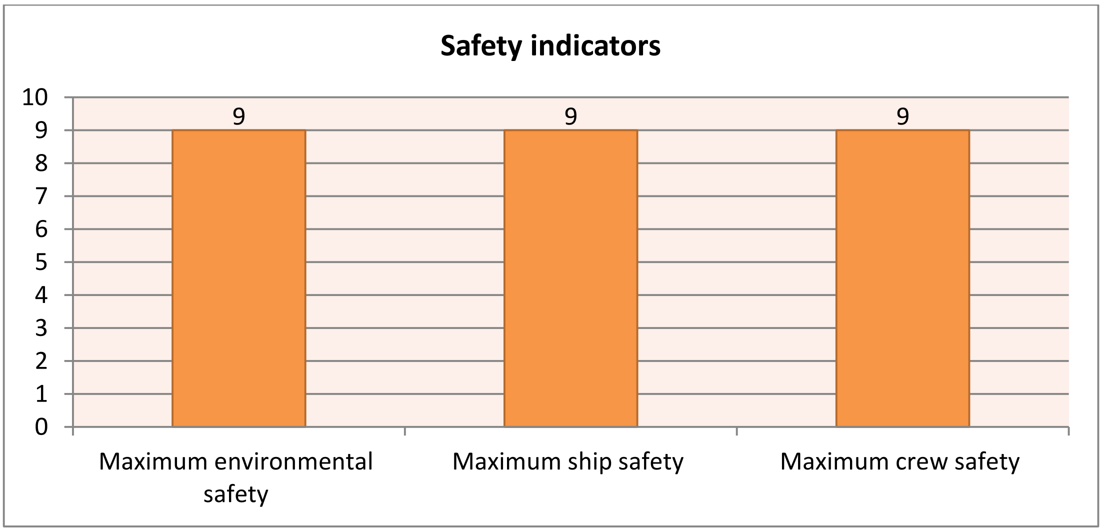

Figure 4-3: The importance the safety indicators

- All of the regulation indicators are considered important i.e. the minimum effect to change of seawater chemistry and the minimum effect to change of seawater clarity criteria scored the highest (8 out of 9), followed by both the minimum effect to change of seawater temperature indicator and the minimum effect to change of seawater salinity indicator (7.25 out of 9) Figure 4-4.

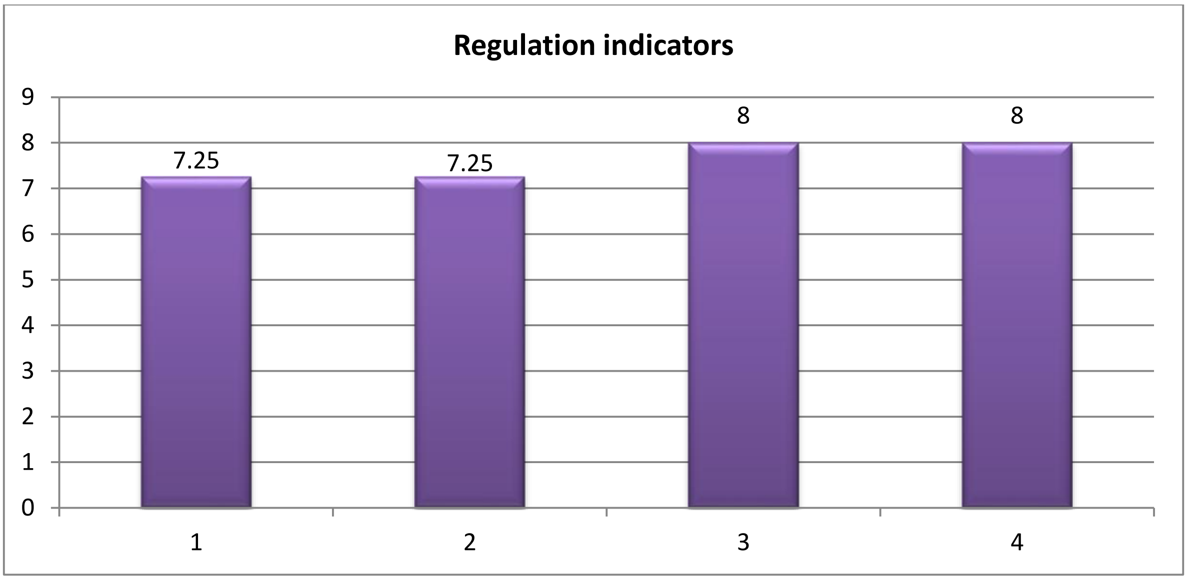

Figure 4-4: The importance of each regulation indicators; 1: Minimum effect to change of seawater temperature; 2: Minimum effect to change of seawater salinity; 3: Minimum effect to change of seawater chemistry; 4: Minimum effect to change of seawater clarity.

Both, the maximum ability to treat ship ballast water capacity indicator and the maximum ease of operation scored the highest with the former scored more at (8.75 out of 9), followed by latter at (8.25 out of 9) respectively; followed by the minimum ship operating cost indicator at (8 out of 9); next the satisfying process time indicator scored (7.75 out of 9) and finally both the satisfy limited space and minimum interruption to ship emergency system scored (7.5 out of 9), see Figure 4-5.

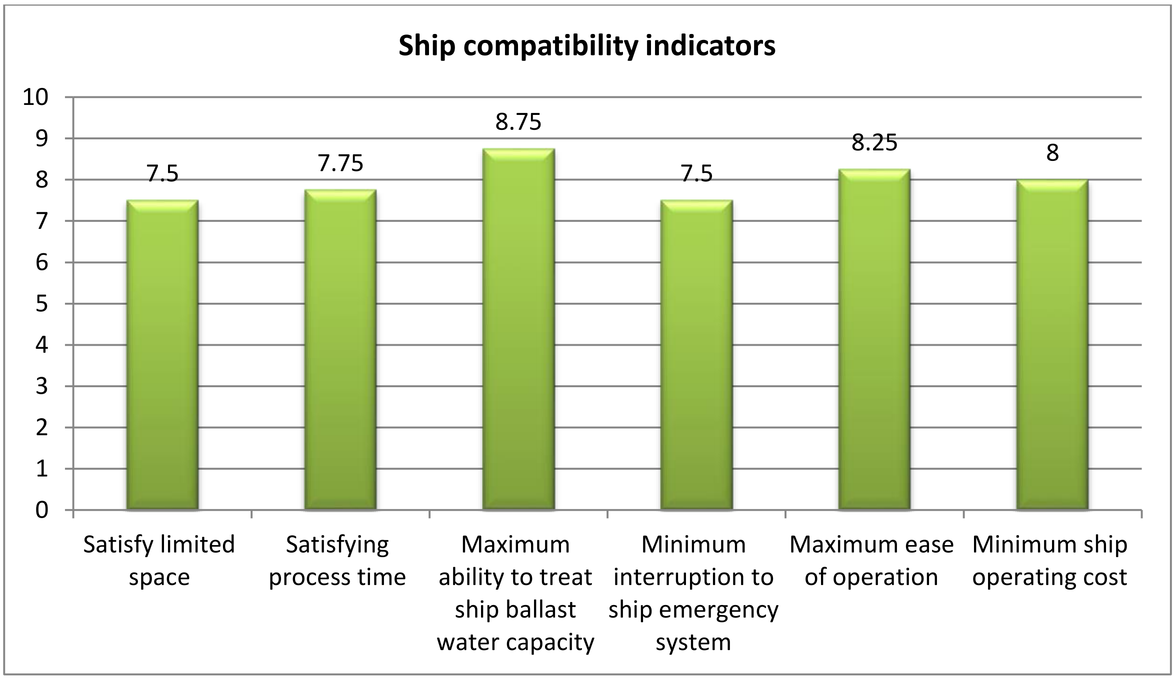

Figure 4-5: The importance of the ship compatibility indicators

From the above results, it can be concluded that the four criteria, which were ranked in average between 7.5 to 9, are almost equally significant and should be considered when selecting a ballast water treatment system. In addition, all the sixteen indicators, which were ranked in the range between 6.25 to 9, are also equally considered significant and thus should be considered when selecting between the given BWTS alternatives for any ship.

In the **fourth question** the interviewees were asked to list any other criteria and indicators that should be taken into account when selecting between BWTS?

One interviewee added the following: *“Retrofit cost, new ship or old ship and ship age should be considered).*

Another interviewee said*: “Reputation of the vendor, on-board testing facility for the standards; power required versus available; less ship equipment’s; ship types and class”.*

Another interviewee said*: “Reputation of the vendor, ship owner experience factor”.*

Another interviewee said*: “Known maker versus unknown maker; equipment reliability”.*

Therefore experts added that there are other key indicators that should be considered in selecting BWTS such as vendor reputation, on-board testing facility and equipment reliability.

In the **fifth question** the interviewees were asked if the above criteria should be used as a measuring tool for selecting between BWTS for any given ship.

All interviewees agreed and said: *“Yes”* to the above criteria and indicators. Therefore the criteria used in the model are validated based on the experts experience and opinion.

4.3.2.4 Section D: Added ship related parameters

In the **first question** a table was shown to the interviewees which have listed the added ship related criteria and indicators that were acquired from the literature.

Table 4-2: Added ship related criteria

Ship related criteria	Indicators
1. % of ballast leg	• Percentage of sea time cargo loaded per year • Percentage of sea time empty cargo run per year • Percentage of port time per year • Percentage of dry dock (for maintenance) time per year
2. Ship Age	• New (e.g. 1-8 years) • Middle aged (9-15 years) • Old (e.g > 16 years)

The interviewees were then asked to give their opinion if these criteria are relevant to affect the decision of selecting a BWTS?

In order to understand the response from the experts, the "Yes" answer was denoted to score "1" and the "No" answer was denoted to score "0".

- The percentage of ballast leg criterion scored the highest (1 out of 1), however, the ship age criterion scored (0.75 out of 1) Figure 4-6.

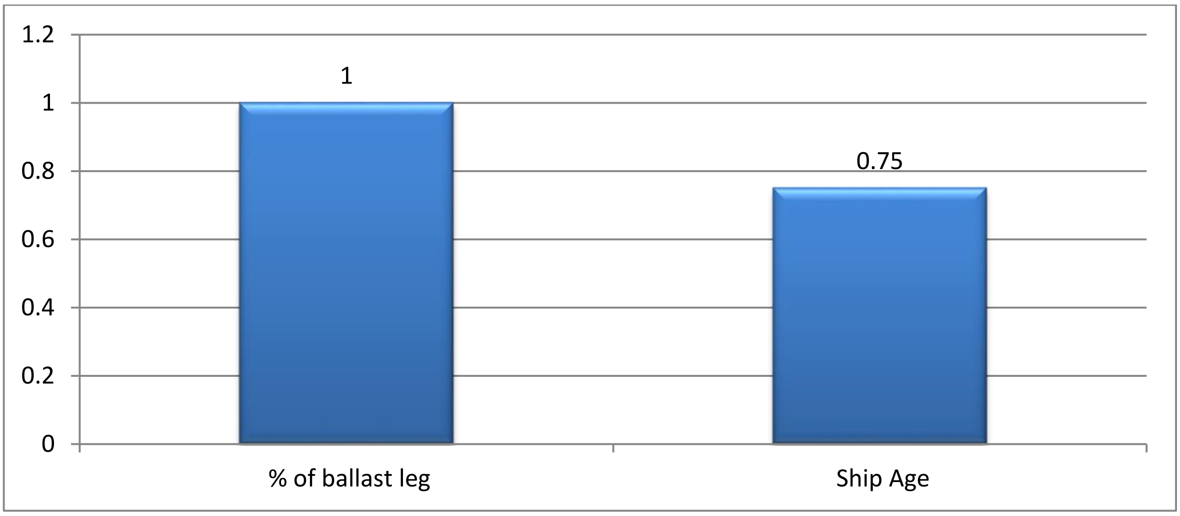

Figure 4-6: the relevance of ship added criteria to affect decision of BWTS selection. "1": denoted for "Yes" answers; "0" denoted for "No" answers

From the above result it is clear that most of interviewees agreed on the relevance of the percentage of ballast leg. However, some interviewees did not agree on the ship's age as an indicator.

In the **second question** the interviewees were asked to rank the importance of each indicator from 1 to 9, and the highest rank i.e. 9 represents the most important criteria and indicator. Definitions of the criteria and indicators were presented to the interviewees in order to prevent vague meanings and make sure they do understand each criterion (Definitions are provided with the interview sheet in appendix A).

- The percentage of ballast leg criterion scored the highest (5.5 out of 9), followed by the ship age criterion with (4.75 out of 9) Figure 4-7.

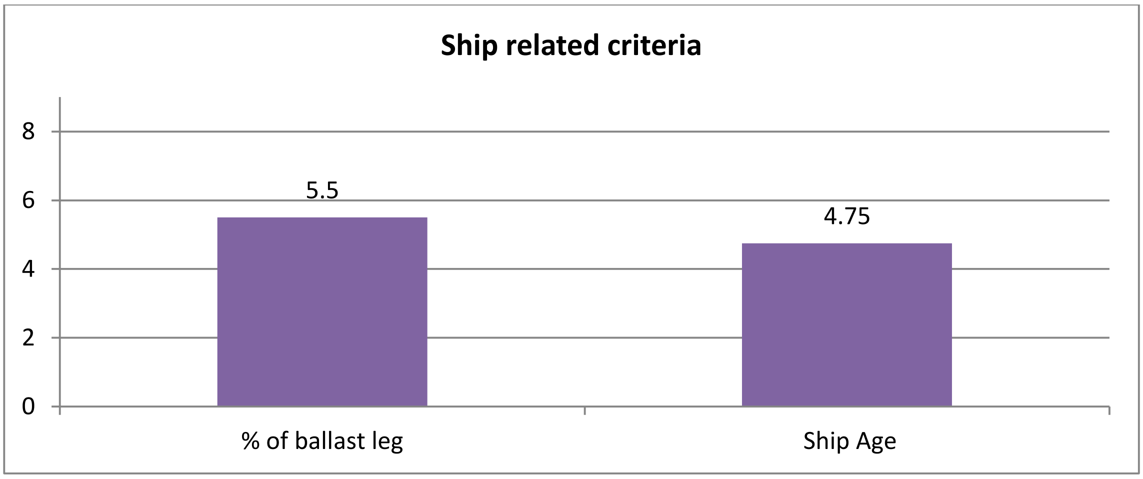

Figure 4-7: The importance of the added ship related criteria

- The percentage of port time per year scored the highest (7 out of 9), followed by both the percentage of sea time cargo loaded per year and the percentage of sea time empty cargo run per year with (6.25 out of 9); cost at (7.75 out of 9) and finally the percentage of dry dock (for maintenance) time per year scored the lowest of them all (5.25 out of 9) see Figure 4-8.

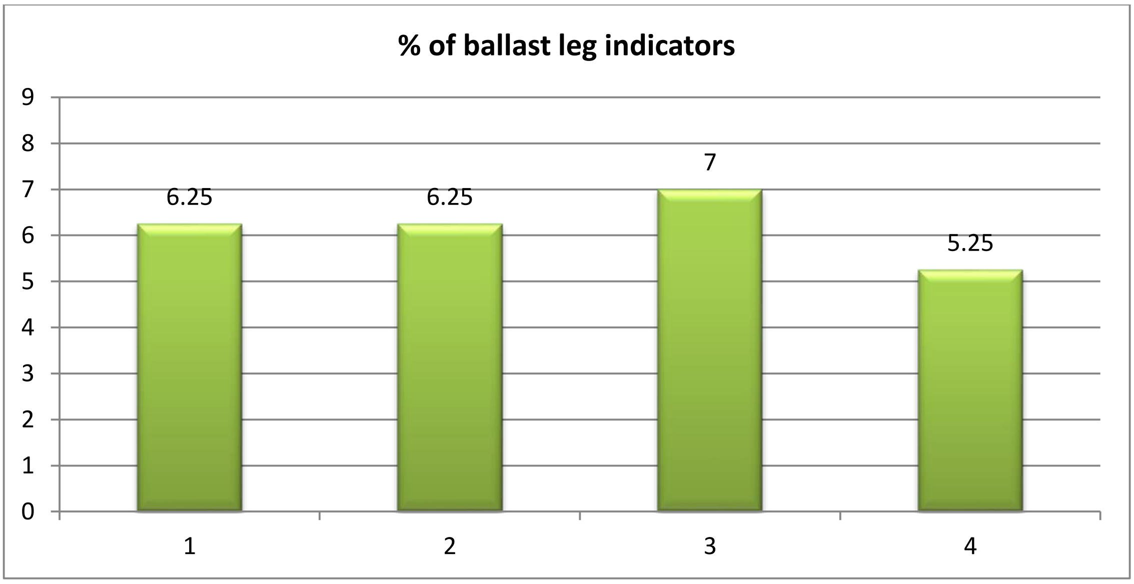

Figure 4-8: The importance of the percentage of ballast leg's indicators. 1: Percentage of sea time cargo loaded per year; 2: Percentage of sea time empty cargo run per year; 3: Percentage of port time per year; 4: Percentage of dry dock (for maintenance) time per year

- The new (e.g. 1-8 years) indicator scored the highest (5 out of 9), followed by the middle aged (9-15 years) scored (4.75 out of 9) and old (e.g. > 16 years) scored the lowest (4.5 out of 9), see Figure 4-9.

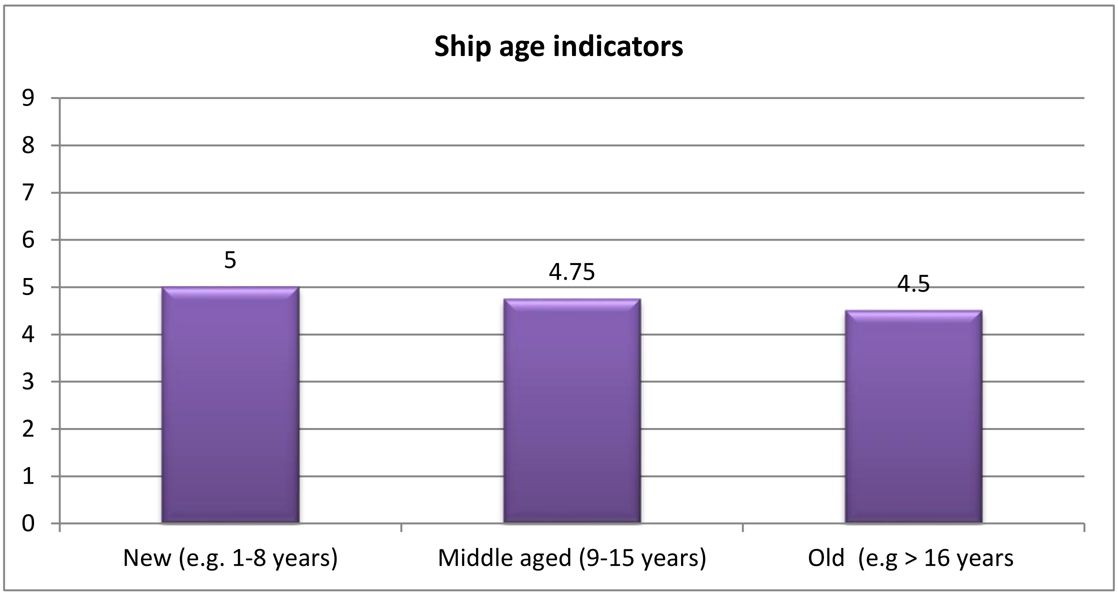

Figure 4-9: The importance of the ship age's indicators

From the above results, it can be concluded that these two added ship related criteria, which were ranked in average (4.75 to 5.5), are not significant and thus it's up to each decision maker whether to consider them when selecting a ballast water treatment system. In addition, all the seven indicators, which were ranked in the range (4.5 to 7), are also not considered significant, because of the low scores. Therefore, it's up to each decision maker whether to consider them or not when selecting a ballast water treatment system for any given ship.

In the **third question** the interviewees were asked if the above criteria should be used as additional measuring parameters for selecting between BWTS.

Not all the experts agreed that these added ship related criteria of a significant importance to be used as additional parameters for selecting between BWTS. However, some have agreed that they should be used. These variations in the views between experts on this particular mater were very interesting, because there is a relation between the ballast water and leg trip versus capacity.

In the **fourth question** the interviewees were asked if they can add any additional ship related criteria and indicators that should be used for selecting BWTS.

Experts, who were interviewed, added other indicators considered such as ballast water coatings, operating profile, and ship type when selecting a BWTS for a given ship. For example, one expert said*: "ship type and ship operating profile can also be added as criteria".* Another expert said*: "ballast water capacity, process time".* Another expert said: *"*ballast *tank coating*". Another expert said: *"*flexibility *between new build versus existing ship and retrofit"*.

4.3.2.5 Section E: Close

In the **first question** the interviewees were asked if they can add any other information needed to develop a tool for selecting a BWTS.

All the interviewees did not comment much on this question and did not add or remove any criteria.

In the **second question** the interviewees were asked about any information or data that is not available to them, and they think that will help the company select a BWTS.

All interviewees had different aspect on the information or data needed and was not available to the shipping company and they've thought that it will help their company to select a BWTS for their ships. For example, one interviewee said: *"ballast water vendors do not provide us with the optimum parameters for our ships. for example, they do not provide the reasons why using 40 micro mesh type of filter and not 100 micron, they also do not provide us with the associated costs, if we choose a filter with a flashback type its cost can be three times higher compared to the one without flashback".*

Another interviewee said*: "The BWTS vendors do not provide the exact or approximate capital, maintenance or operating cost of their equipment. For example, no cost was provided of the filter type with or without backflush".*

Another interviewee said: *"The paint manufacturers do not give guarantees on the effects of any particular BWTS on the ballast water tank coatings. If such a guarantee was provided then shipping companies would be less hesitant in widening their options for selecting BWT".*

Another interviewee said: *"Every ballast water vendor supports his own treatment which have received a type approval certificate; however, no information to distinguish which one is better BWTS and lower biasness".*

Another interviewee said: *"We do not know if there will be more regulations and IMO standards to be met in future; can the existing BWTS be upgraded or rectified to meet any future standards. For example, nowadays they would like ships to lower emissions and this requires upgrading to our existing engines to burn cleaner fuel, if this will happen to the BWTS then we should be more worried not to select a ballast water treatment system that cannot be upgraded".*

From the above replies, it was understood that some transparency issues between the shipping companies, ballast water vendors, paint manufacturers, and class societies exist. In addition, having more strict standards by other countries is worrying shipping companies as it may influence the IMO standards and thus shipping companies are less willing to implement a BWTS that cannot meet possible future standards. Further research on the above issues is required; answering how to emerge the shareholders can facilitate solving the issue of the BWTS selections.

4.4 Summary

This chapter discussed and analysed the interviews with the experts from the three different shipping companies. The discussion included the importance of selecting a ballast water treatment system (BWTS); different sources that shipping companies acquire in searching for BWTS information; opinions of each shipping company on the chemical versus other type of BWTS; shipping companies future plans for implementing BWTS; the procedures and the criteria taken into account by shipping companies when selecting BWTS; the existence of a model or tool to support or assist selecting BWTS; evaluations to parameters used for selecting BWTS for a given ship; evaluated the added ship related criteria was also discussed; finally issues of the missing information to shipping companies which could have helped them selecting BWTS were discussed.

4.5 Conclusions learned from the interviews

Form the conducted case study by interviewing twelve experts from the three shipping companies, the finding and conclusions are as follows:

- The challenge of selecting the most suitable ballast water treatment system (BWTS) is an existing issue.

- Selecting the most feasible BWTS is very important to all shipping companies since there are many differences between each type such as cost, safety, power requirement, size etc. Therefore, selecting a BWTS requires taking into account many criteria and parameters.
- Shipping companies do have disputes or differences in their views whether or not their ships have contributed to the issue of bio-invasion caused by ship's ballast water; nevertheless, all shipping companies are willing to comply with international regulation set by IMO BWM Convention when it enters into force.
- Shipping companies varied in their depth of knowledge about the differences between BWTS, most of their information obtained from the ballast water treatment vendor's website, and no indication of obtaining such information from academic journals or conferences.
- All shipping companies rejected the use of active substance type of BWTS such as chemicals, and all agreed to implement non-active substance BWTS such as Ultraviolet (UV) and filtration. This is because, chemicals will affect their ballast tank coating by increasing corrosions and thus may cause ship structure failures.
- Shipping companies are not taking such BWM Convention seriously by implementing BWTS on-board ships, because of the delay of the Conventions and it could also be a technique followed by shipping companies in order to delay it from entering into force. Delays may also be due to the challenges that shipping companies are facing with such a selection decision. Another reason could be that they do not trust BWTS technologies in meeting the future standards.
- Depending on the size of each shipping company, the decision of selecting BWTS is normally made by one decision maker who is normally the head of the technical fleet department.
- Although shipping companies are aware of the many and complicated criteria that should be considered when selecting a BWTS, yet, they have got no tool or model to assist them to select BWTS for their ships.
- Shipping companies will find such a decision tool or model useful because it will save them time and money, lowers their efforts on research, reduce human error, and help decision makers making decision when dealing with complexities of different parameters or criteria. This may not apply to smaller shipping companies.

- The criteria and indicators listed and were used by developed AHP model were found very interesting from the interviewee’s point of view.
- Experts validated by agreeing on the importance of the criteria and indicators or parameters to be considered as a tool for selecting the most feasible BWTS for any given ship.
- Experts have recommended combining the Bio-efficacy into the Regulation as one single criterion as they both served the same purpose in the proposed model. Based on the latter point, the interviewer asked the interviewees to evaluate only one in order to define the importance of the combined criterion. This has slightly amended the developed model into the final model Figure 4-10.
- Based on their experience they evaluated the importance of the criteria and indicators and it was concluded that the four criteria which were ranked in average between (7.5 to 9 out of 9) are equally significant and should be considered when selecting a BWTS. The sixteen indicators, which were ranked in the range between (6.25 to 9 out of 9) are also equally important and thus should be considered when selecting between BWTS for any given ship.
- Shipping companies suggested other criteria such as vendor reputation, retrofit costs and reliability. However, due to the time constraints they were not added into the model and were recommended for future studies.
- Shipping companies evaluated the percentage of ship’s ballast water leg as more acceptable to be added as a ship related criteria which may influence the decision about the selection of BWTS than ship’s age. However, based on the ranked average between (4.75 to 5.5), it was concluded that the two added ship related criteria which are not significant and thus it’s up to the future user to consider them when selecting a ballast water treatment system. The same case for all the seven indicators, which were ranked in the range (4.5 to 7), is not considered significant and thus it’s up to the decision maker or future user to consider them when selecting a ballast water treatment system for any given ship.
- Transparency issues between the shipping companies, ballast water vendors, paint manufacturers and class societies do exist. It will be useful for future studies to investigate possible ways to minimise such issues.

- Strict standards by some countries are worrying the shipping companies as they may influence the IMO standards and thus shipping companies are less willing to implement a BWTS which cannot meet the possible future standards.
- Based on literature review and interviews, several criteria have been aggregated to be used to compare between different BWTS for any given ship in Table 4-3.

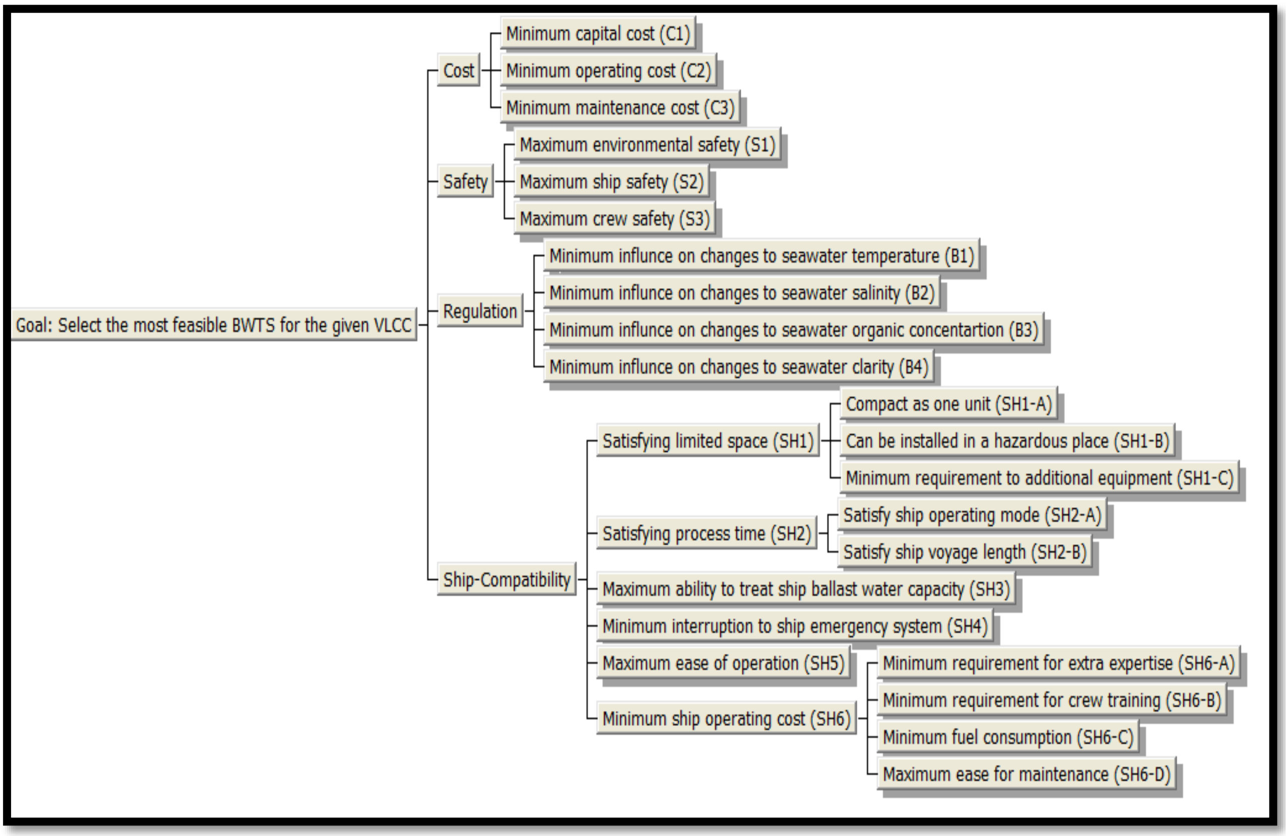

Figure 4-10: The final hierarchy structure of the developed model.

In Figure 4-10 the intention of the developed model is to help decision makers to select the most feasible BWTS for their ships. As shown in Figure 4-10 the ultimate goal of the developed AHP model is shown on the left-hand side, i.e. select the most feasible BWTS alternative for the ship. The most feasible BWTS is meant to be the ballast water treatment system alternative which obviously satisfies by weighting/scoring more against the identified criteria by considering both identified ballast water related criteria and ship related criteria. The global criteria are shown in the (2nd level) to the right hand side of the ultimate goal namely: cost, safety, regulation and ship-compatibility. Then sub-criteria or indicators/parameters are shown to the right hand side of the global criteria as shown in the (3rd level). The cost is divided into three sub-criteria (objectives) namely: minimum capital cost (C1), minimum operating cost (C2), and minimum maintenance cost (C3). The safety is divided into three sub-criteria (objectives) namely: maximum environmental safety (S1), maximum ship safety (S2), and maximum crew safety (S3). The regulation is divided into four sub-criteria (objectives) namely: minimum influence on changes to seawater temperature (B1), minimum influence on changes to seawater salinity (B2), minimum influence on changes to seawater organic compound (B3), and minimum influence on changes to seawater clarity (B4). The ship compatibility is divided six sub-criteria (objectives) namely: satisfying limited space (SH1), satisfying process time (SH2), maximum ability to treat ship ballast water capacity (SH3), minimum interruption at ship emergency (SH4), maximum ease of operation (SH5), and minimum ship operating cost (SH6). Then the sub sub-criteria or indicators/parameters are shown in the (4^{th} level): satisfying limited space (SH1) is divided into three indicators namely: compact as one unit (SH1-A), can be installed in a hazardous place (SH1-B), and minimum requirement to additional equipment (SH1-C); satisfying process time (SH2) is divided into two indicators namely: satisfy ship operating mode (SH2-A), and satisfy ship voyage length (SH2-B); and minimum ship operating cost (SH-6) is divided into four indicators namely: minimum requirement for extra expertise (SH6-A), minimum requirement for crew training (SH6-B), minimum fuel consumption (SH6-C), maximum ease for maintenance (SH6-D).

It is worth noting that, all the parameters/criteria and indicators shown in Figure 4-10 are the required inputs to the developed model. This is necessary to obtain the ultimate output of this model which is to compare between any given BWTS alternatives for a given ship in order to select the most feasible alternatives.

Table 4-3: Criteria should be considered when selecting a ballast water system for a given ship

Identified Criterion	Source
1. Required freight rate (RFR) 2. Costs (retrofitting/installation) 3. Environmental pollution 4. Safety 5. Fuel efficiency 6. Pollution 7. Biological efficiency	(Perakis and Yang, 2003)
1. Regulation 2. Safety (ship/crew) 3. Practicality 4. Costs 5. Certification and approval	(Rigby, 2004)
1. Particle removal efficiency 2. Net ballast flow 3. Arrangement 4. Maintainability	(Parsons, 2003)
1. Benefits	(Mamlook et al., 2008)
1. Time frame	(Gomes, 2005)
1. Environmental sustainability index 2. Economical sustainability index 3. Social sustainability index	(Basurko and Mesbahi, 2012)
1. Efficacy on micro-organisms 2. Efficiency on organic 3. Adaptability to harsh environment 4. Human risk 5. Ecological risk 6. Waste production	(Jing et al., 2013)
1. Ballast water related criteria: (Cost, Safety, Bio-efficacy, Regulation, Practicality) 2. Ship related criteria: (Operating mode, Ship size, % of ballast leg, ship operating cost, voyage length, Geographic location of voyage)	ALHababi et al (2014)
1. Ship compatibility	ALHababi et al (2014)
1. Gas proof design	(Satir, 2014)
1. Vendor reputation and quality 2. Minimum retrofit cost 3. System simplicity 4. Simplicity of maintenance 5. System ability to be upgraded (meet future standards) 6. Paint manufacturer's warrantee & support 7. New build vs. retrofit	Interview

Chapter 5 will discuss the data collection and aggregation of the required information by the developed model.

Chapter 5: Data Collection and Aggregation of the Required Information

5.0 Introduction

This chapter focuses on how the developed model is applied into an actual case study. The collection of the data required by the model is discussed. The type of data used in this research and how they were evaluated are also discussed in this chapter before more in-depth data analysis in chapter 6.

Due to the nature of this study a combination of three datasets are aggregated to form the required information (input data) of the developed model:

1. Data from a real ship under normal voyage;
2. Technical information for each of the Ballast Water Treatment Systems (BWTS) alternatives from the vendors' websites; and
3. Expert evaluations for the relative importance of each identified criteria in the decision support model.

The weights or evaluations of the criteria used in the decision support model are collected through a web-based questionnaire (first hand) data collected from an identified decision maker from a shipping company who is responsible (hold authority) for the selection of a ballast water treatment systems (BWTS) for this shipping company. The expert was emailed the criteria weighting questionnaire in August 2014, the criteria weighting questionnaire is attached in the Appendix B, which also provided a guiding example and definitions for the expert to minimise the misunderstanding when answering the questionnaire by selecting the appropriate importance.

Seven Ballast Water Treatment Systems (BWTS) alternatives were randomly selected for the purpose of this study. It was not possible to acquire data from the BWTS vendors as they treat their systems as a highly confidential information. Therefore, the BWTS information (second hand data) was gathered from the published information by each BWTS vendor website or their advertised catalogues or brochures. It is worth noting that missing data which were acquired from the relevant literature review. In addition, it is important to note that the availability of the data, time constraint of this study, and the budgets were the limiting factors for the number of the selected BWTS alternatives.

Therefore, these seven BWTS alternatives are the objects of the evaluation in this study to assess the applicability of the developed model to feasibly select the alternatives which satisfy all the objectives for a given ship.

Finally, the data and voyage information of the Very Large Crude Carrier (VLCC) tanker was acquired from a well-known oil shipping company. However, to increase the analysis of the study, the voyage of the VLCC has been changed in order to observe the sensitivity of the model by the changes of the selected BWTS alternatives.

5.1 Data aggregation flowchart

This section considers how the data were aggregated in a schematic flowchart Figure 5-1.

To summarise the steps used in Figure 5-1 for collecting and aggregating the required information in this study are as follow:

- Firstly, the data related to each BWTS alternative were collected from the BWTS advertised' website and catalogues. The missing information needed to evaluate some BWTS criteria were acquired from the literature review of relevant studies.
- Secondly, the VLCC characteristics and voyage information were collected from a well-known shipping company, which was kind enough to provide the information/data of one of their VLCCs and its voyage as required by the developed AHP Model.
- Thirdly, the information of each BWTS and the VLCC characteristics were aggregated then evaluated based on the availability of the required information. Otherwise, subjective evaluation along with scoring using the 1-10 scale was used by the author based on the information and the understanding of their suitability to satisfy the objective of each criterion accordingly.
- Fourthly, the preferences of the importance of each identified criterion were obtained from a decision maker (the personnel who hold the authority) for selecting a BWTS

for their company's ships through the developed web-based criteria weighting questionnaire (Appendix B).

- Fifthly, all the information which were used as inputs to the developed decision model are decomposed based on each identified criteria in order to derive the results to select the most feasible ballast water treatment system (BWTS) for the given ship.

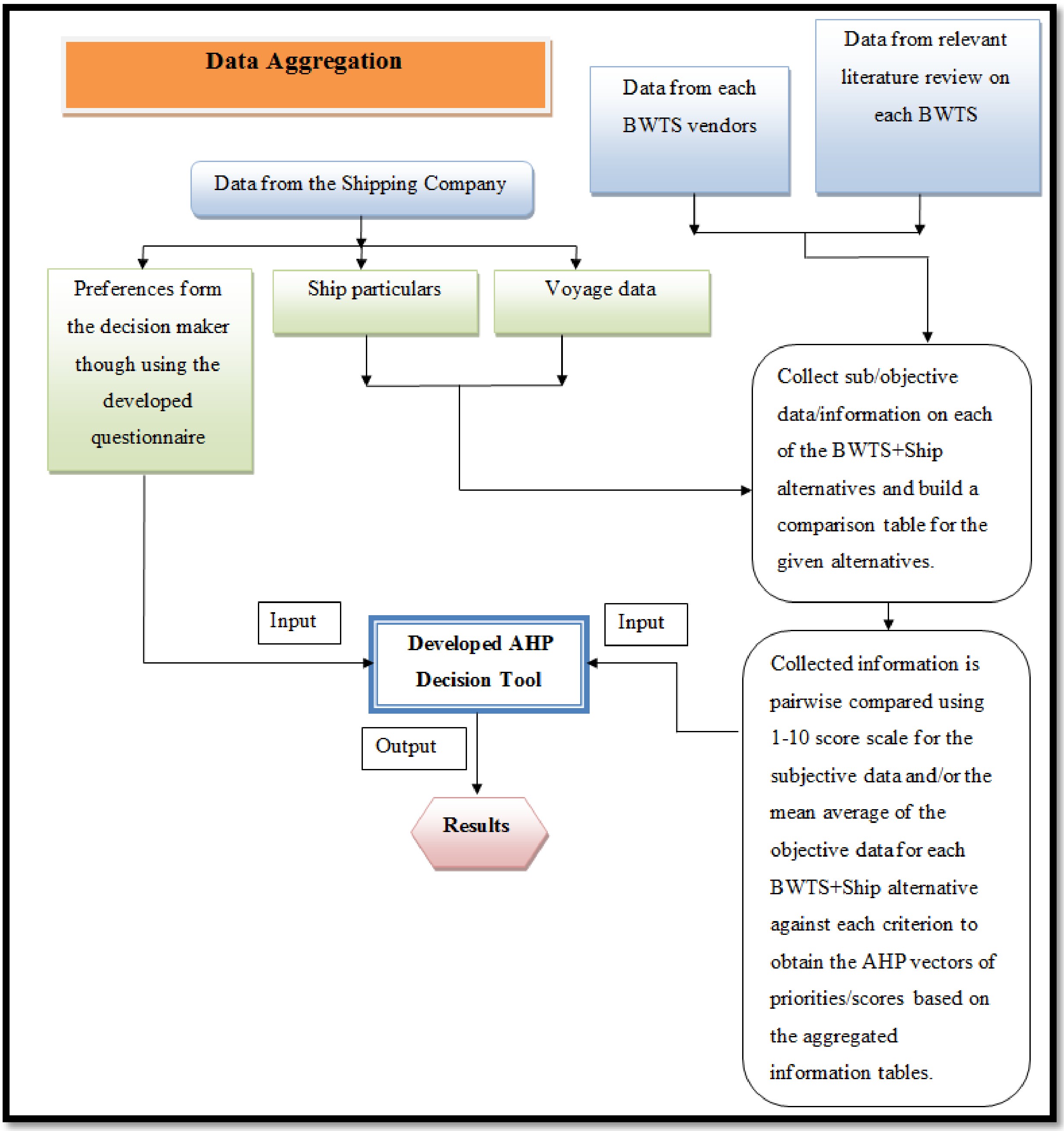

Figure 5-1: Data aggregation flowchart

5.2 Case study and model set up

In any shipping company with international seagoing ships in particular, the compliance with the IMO rules and regulations are very important in order to ensure that their ships are seaworthy. The incoming international IMO convention for ships to manage their ballast water through regulation D-2 (performance standards) is more emphasised on by the IMO BWM Convention for ships to continue their international business without facing sanctions for not complying with the BWM Convention.

According to the information collated from the interviews of the case study with experts from different shipping companies; the existence of the challenge and the issue to select the most feasible ballast water treatment system is found as one of the important real life problems confronting shipping companies today (see Chapter 4 for more details). This is because of the many parameters both tangible and intangible that shipping companies are required to carefully consider. In addition, the complexity of making such a decision is that there are many types of ballast water treatment systems (BWTS) available in the market without any model or tool to assist the decision makers to make better decisions. It is worth remembering that although all these BWTS are approved by the IMO and obtained their type approval certificate by their administrations, they also vary in the characteristics (e.g. power requirement, cost etc.) making such a problem a very critical as one BWTS alternative could be more advantageous than the other one. Therefore, taking into considerations all the important criteria for making a better decision is very important in order to decide on the trade-offs between the alternatives when selecting a BWTS for their ships which is expected a life equals to the ship's life.

Unanticipated decisions are likely to have a significant negative impact on the management of the ship operations in the long run. Therefore, selecting the most feasible BWTS should be verified in a more systematic way by a mathematical approach in order to achieve the desired solution. In order to solve this problem systematically, the AHP decision support model was developed to take into account both tangible and intangible criteria for making decision on several BWTS alternatives for a given VLCC from a well-known shipping company.

Seven Ballast Water Treatment systems (BWTS) alternatives were randomly selected for the purpose of this study. Second hand data about each BWTS was acquired from the published information by each ballast water treatment system's vendor website and/or their advertised catalogues or brochures. Due to the time and budget constraints, the missing data were acquired from other relevant literature review or approximated based on the understanding of each alternative.

The seven ballast water alternatives are the objects of evaluations in this study to evaluate their feasibility as BWTS alternatives for the VLCC. The VLCC particulars and voyage data were acquired from a well-known shipping company. However, to increase the analysis of the study, the voyage of the VLCC tanker has been simplified in order to observe changes of selected BWTS alternatives.

5.2.1 Ship particulars

Information of a typical VLCC were provided by a well-known oil shipping company. The VLCC particulars are shown in Table 5-1.

Table 5-1: Information acquired for a VLCC from a well-known oil shipping company

Ship information	
Ship Size (deadweight)	317,250 MT
Design speed (knots)	15
Sea Margin	5%
Voyage speed (knots)	14.95
Length overall (meters)	319
Type of cargo	Crude oil
Moulded breadth (meters)	60
100% cargo capacity (m^3)	351,760
100% Ballast water volume (m^3)	102311.8
Ballast water capacity	Two 2 x 3,000 m^3/h (one steam and one electric) each at 35 meters of water column (MWC)

5.2.2 Voyage data

The VLCC voyage data were simplified to cope with the developed model as presented in Table 5-2. In Table 5-2, the temperature differences between the regions were acquired from (weatherbase, 2014). The salinity approximations were acquired from (NASA, 2014). In real world, VLCCs normally runs under a time charter or voyage charter contracts in a way to deliver cargo from the loading ports to the unloading ports wherever they find cargo. Therefore, no particular route or port they are obligated to load or unload cargo from; hence they sail wherever there is a demand driven by the market if the harbor can accommodate its size and draft. However, it was assumed for simplicity reason, that this VLCC spends 6 days in port for loading cargo and 6 days for unloading and sails between two voyage legs (Kuwait-Huizhou, China). It was also assumed that the VLCC is fully loaded in one leg and fully ballast in the return between the given ports.

Table 5-2: VLCC voyage information: loading and unloading regions, cargo operation, voyage length, temperature differences, and salinity approximations.

ports legs	cargo operation	Sailing distance (nautical miles)	days at sea	days in port	Region	Ave. low temp (˚C)	Ave. high temp (˚C)	approx. Salinity (g/kg)
Middle East to Far East	Loading	5271	14	6	Kuwait	19	32	35.5 - 36.5
	Discharging			6	Huizhou	15	22.4	34 - 34.5

It is worth to note that during the fully loaded voyage, there is no significant amount of ballast waters onboard the VLCC; the problem of ballast water is when unloading cargo from the cargo holds and filling the ballast tanks with seawater simultaneously. In this case, the ballast water tanks are filled with harmful organisms, and treatment to this ballast water is necessary before reaching the new port for loading cargo again and emptying ballast water tanks at the loading port to allow more cargo in the cargo's holds. Therefore, when the VLCC unloads cargo in China, it fills in ballast water tanks in order to maintain the required safe operation under various weather conditions by adjusting the trim while maintaining the optimum speed of the ship before it reach Kuwait port fully ballasted. The VLCC spends 14 days before it reach back to Kuwait in order to reload cargo.

The average high and low seawater temperatures difference between Kuwait and Huizhou as a geographic locations ports (e.g. average low seawater temperature difference between the two locations is 4˚C i.e. 19˚C - 15˚C = 4˚C; average high seawater temperature difference between the two locations is 9.6 ˚C i.e. 32˚C - 22.4˚C = 9.6˚C) Table 5-2.

5.2.3 BWTS data

Collecting information from the ballast water treatment vendors is the second set of data which is very important and required by the developed model. Several attempts and emails were sent to many BWTS vendors however, they declined to provide the required information because of confidentiality reasons. Therefore, in this study, both subjective and objective information needed were gathered based on the BWTS vendor's website. Missing data were acquired from the relevant literature in order to complete the study.

In order to allow proper comparisons, it is important to note that the selected systems had to meet the following:

- The VLCC ballast water pump capacity,
- Comply with the IMO standard D-2, obtained type approval by their administration and/or IMO when it is proper.

The Seven BWTS and their utilised method of treatment are presented in the Table 5-3.

Table 5-3: List of the ballast water treatment systems (BWTS) and their disinfection method

Ballast Water Treatment System (BWTS)	Disinfection method
BWTS1	De-oxygenation
BWTS2	Ozonation
BWTS3	Chlorine Dioxide
BWTS4	Chlorination
BWTS5	Ultraviolet (UV) irradiation
BWTS6	Ultraviolet (UV) irradiation
BWTS7	Ultraviolet (UV) irradiation

More details about the aggregated information of each of these seven BWTS in Table 5-3 and how they were evaluated will be discussed in the next sections in this chapter.

5.2.3.1 De-oxygenation (BWTS1)

De-oxygenation of ballast water treatment system induces a low-oxygen (hypoxic) condition in ship ballast tanks using inert gas Figure 5-2. This produces a hypoxic condition that claimed to forbid aquatic organisms (both plants and animals). This is because of the low-oxygen for the organisms to survive. This low-oxygen environment also limits the amount of oxygen available to form iron oxide, or rust, thereby protecting the internal steel surfaces of the ballast tanks against corrosion and preventing premature deterioration of ballast tank coatings.

An Inert Gas Generator (IGG) is employed in the system without filter by means of venturi injectors in to the ballast water line. The dissolved oxygen in the ballast water is claimed to be stripped out of solution, leaving the ballast water deoxygenated and effectively sterilised. When de-ballasting, ballast tanks are filled with inert gas to maintain a low oxygen environment. This activity is claimed to reduce corrosion and coating breakdown in the ballast tanks.

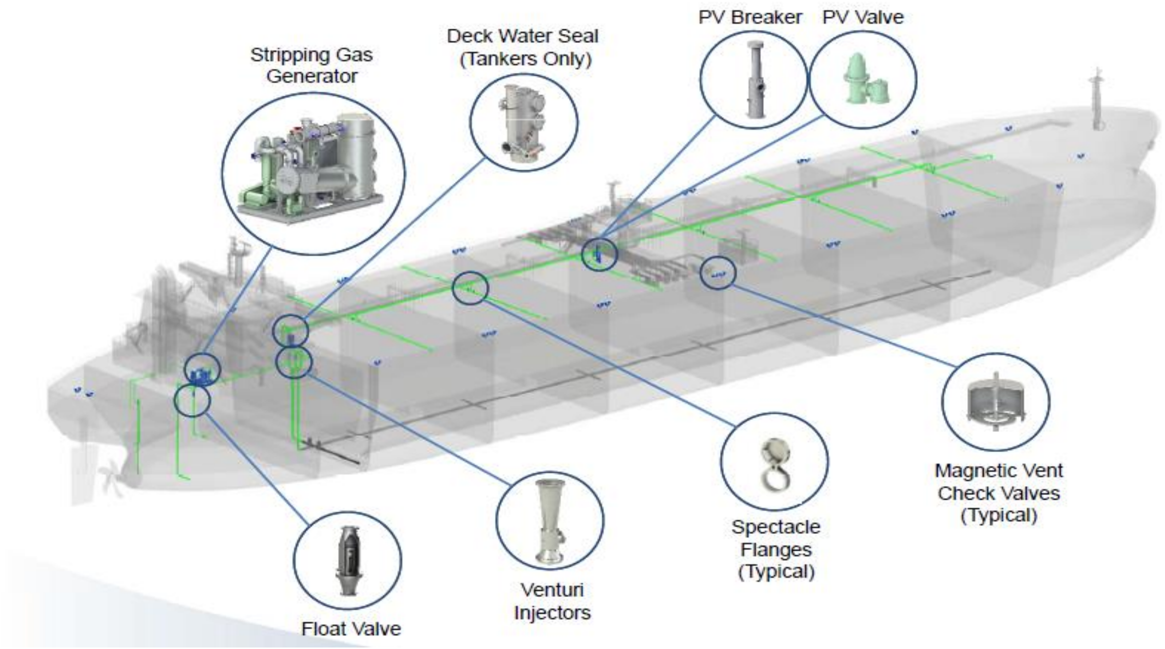

Figure 5- 2: Typical De-oxygenation ballast water treatment system on ships (System, 2015)

Key advantage according to the vendor:

- De-oxygenation is the only BWMS that can make a significant cost saving for protecting ballast tank coatings, sacrificial anodes, and steel structure against the effects of corrosion.
- The system significantly reduces the cost of coating maintenance and repair, and protects exposed steel between dry dockings.
- The system shows significantly reduced corrosion rate up to 84 %.
- The deoxygenation process provides ballast tank corrosion protection equivalent to sacrificial anodes, and can save hundreds of thousands of dollars over the life of a ship.
- The system is safe for coatings and steel.
- The system safely maintains a low-oxygen environment where aquatic organisms cannot survive.

- The system requires no filters. And it always work in fresh, salt, cold, muddy or polluted water.
- The Stripping Gas Generator (SGG) can replace the topping generator of crude oil tankers (approved by ABS) and can be designed to handle cargo inerting for LNG and product tankers. This can save hundreds of thousands of dollars to ship-owners.

System components:

1. Stripping Gas Generator. (SGG can be located anywhere aft of engine room bulkhead)
2. Deck Water Seal (Tankers Only).
3. P-V Breaker & P-V Valve (P-V: pressure volume)
4. Float Valve
5. Venturi Injectors;(venturi injectors can be located in any space, including forward ballast tanks)
6. Spectacle Flanges (Typical)
7. Magnetic Vent, Check Valves (Typical)

Ballast operating sequence:

1. Ballasting:

a. The SGG turns on and sends low-oxygen inert gas to venturi injectors.
b. Ballast pumps, then send ballast water through the venturi injectors.
c. Cavitation with inert gas creates micro fine bubbles emulsion in water.
d. Dissolved oxygen diffuses from the liquid phase into the gas phase bubbles

2. De-ballasting:

a. During de-ballasting, the re-oxygenation operation upon release is rapid. Upon discharge below the water line, the ballast water once again passes through the venturi injectors, where air is re-introduced back into the water before release into the environment.

b. As water exits from the ballast tanks, they are filled with inert gas in order to maintain a low-oxygen condition, which has two key **benefits**:

- When deoxygenated water is once again drawn into the ballast tanks, it will not re-oxygenate.
- Ballast tank coating life is extended and steel corrosion is reduced by up to 84%.

More information about BWTS1 is gathered in Table 5-4.

Table 5-4: BWTS1 parameters

BWTS1	Information by BWTS Vendor website, catalogue
Type of Treatment	Deoxygenation + Cavitation
Use of chemicals	No chemicals
Active substance use	No
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	To above 6000 m^3/h.
Sensitivity to seawater salinity	Not sensitive
Sensitivity to seawater temperature	Not sensitive
Sensitivity to seawater chemical property	Not sensitive
Safe to ship	No risk to ship plus it reduces corrosions rate in ballast water system
Safe to crew	Not provided
Safe to environment	No risk to environment
Process time	Not provided
Power/consumption	24 kW for 500 m^3/h ;48 kW per 1000 m^3/h; 258 kW for 6000 m^3/h
Footprint	Not provided – approximation of. 5.0m x 2.5m = 12.5m^2
Vendor reputation	very good
System number of components	Seven components (three are major): (Stripping Gas Generator (SGG); Deck Water Seal; PV Breaker & PV Valve; Float valve; Venturi Injectors ; Spectacle Flanges; Magnetic Vent, Check Valves)
Type approval	Yes

5.2.3.2 Ozonation (BWTS2)

BWTS2 uses a shipboard ozone generator which takes ambient air and strips away the nitrogen, concentrating the oxygen content Figure 5-3. After that it passes the oxygen content through a high frequency electrical field to produce ozone (O_3). The ozone is then injected into the incoming ballast water to oxidize and neutralize entrained aquatic species. Ozone has an extremely short half-life and it is one of the most powerful oxidizing agents produced. Ozone is proven as an effectively neutralizing endo-toxin, viruses, bacteria, fungi and organic material rapidly. For this reason, ozone has been widely used in the medical sterilization and water treatment industries for many years.

When ozone is injected into influent ballast water, a percentage of the entrained aquatic species are killed by direct contact with the ozone. The remainder are killed or neutralized when the ozone reacts with other chemicals that occur naturally in seawater, to form TROs

(Total Residual Oxidants: hypobromous acid and hypobromide ion), highly effective disinfectants in their own right. Both ozone and hypobromous acid disintegrate extremely rapidly – ensuring that there is no damage to the receiving waters into which the treated ballast water is discharged.

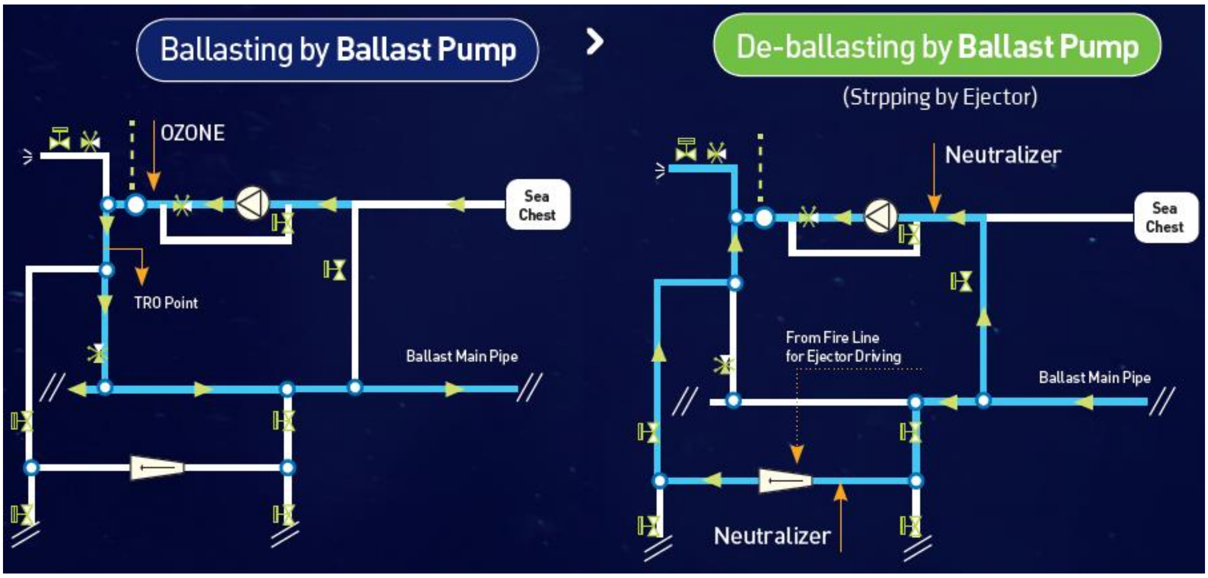

Figure 5- 3: Typical Ozone ballast water treatment system operation on board ships (NK-O3BlueBallast, 2015)

Key benefit according to the vendor:

- Safe & strongest oxidant, disinfectant
- Extremely short half-life time: 5.8 second in seawater, 30 minutes in fresh water and 54 minutes in gaseous state.
- Technically proven system: First used as disinfectant by French municipality in 1899, and installed up to 1,000 for commercial and industrial use.

System components:

1. Oxygen generator - takes ambient air, strips off the nitrogen and concentrates the oxygen to supply the ozone generator.
2. Ozone generator- produces ozone from oxygen passing through high frequency electric field.
3. Ozone injector- diverts incoming ballast water to side stream and injects ozone before ballast water re-enters the main ballast stream. Ensuring high kill rate through optimal dosage of ozone eliminates potential for corrosion.

4. Control & Monitor- variety of sensors, meters, switches and alarms are connected to central control software integrated to ship's overall ballast management system, allowing all aspects of the system to be monitored and controlled and keeping electronically all data on system operation and performance, including automatic safety and cut-off switches.

More information about BWTS2 is gathered in Table 5-5.

Table 5-5: BWTS2 parameters

BWTS2	Information by BWTS Vendor website, catalogue
Type of Treatment	Ozonation
Use of chemicals	yes chemicals
Active substance use	yes
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	150-4000 m^3/h.
Sensitivity to seawater salinity	Not provided
Sensitivity to seawater temperature	Not provided
Sensitivity to seawater chemical property	Not provided
Safe to ship	Not provided
Safe to crew	Not provided
Safe to environment	Not provided
Process time	Not provided
Power consumption	221 kW per 3000 m^3/h ; 70 kW per 1000 m^3/h
Footprint	Total= 29.2 m^2
Vendor reputation	very good
System number of components	Four components: Oxygen Generator; Ozone Generator; Ozone Injector; Control & Monitor
Type approval	Yes

5.2.3.3 Chlorine Dioxide (BWTS3)

BWTS3 generates chlorine-free i.e. chlorine dioxide using hydrogen peroxide (H_2O_2) or Purate, a patent-protected chlorine dioxide generation method Figure 5-4. Hydrogen peroxide (H_2O_2) is a chlorate-based chlorine dioxide generation process. This method differs from other conventional chlorine dioxide generation methods that involves the use of aqueous or gaseous chlorine, making the chlorine-free method environmentally superior. Additionally, Hydrogen peroxide produces chlorine dioxide efficiently, thereby controlling the required input of precursor chemicals and eliminating production of unwanted by-products.

BWTS3 consists of two self-contained chemical storage modules, two separate precursor chemical pumps, a chlorine dioxide generation module (housing for the reactor column), a booster pump, a programmable logic controller (PLC), an operator interface terminal (OIT), a system status/start-up panel, and piping to inject chlorine dioxide solution into the ballast water line. Axillary equipment include pipelines for chemical vents and re-supply, and in-line sampling valves.

With chlorine dioxide generator, individual chemical pumps transfer the hydrogen peroxide (H_2O_2) and sulphuric acid (H_2SO_4) to the reactor column within the chlorine dioxide generation module. The reactor column is under vacuum and is continuously monitored using a pressure transmitter to ensure the generation of chlorine dioxide under sub-atmospheric conditions. Loss of vacuum for any reason (loss of water flow, power, etc.) will automatically shut down the system and stop chlorine dioxide production. Inside the reactor column, the chemicals react to form chlorine dioxide, oxygen, sodium sulphate and water.

During the production or injection of chlorine dioxide there are no chemicals open to the atmosphere. All chemicals are completely contained in appropriate storage ships or pipelines during the entire treatment process. All aspects of the treatment process take place under conditions that are highly controlled and monitored automatically at all times. Chlorine dioxide is generated on demand based on the volume of ballast water being brought on-board and is injected immediately. Chlorine dioxide is not stored on-board at any time.

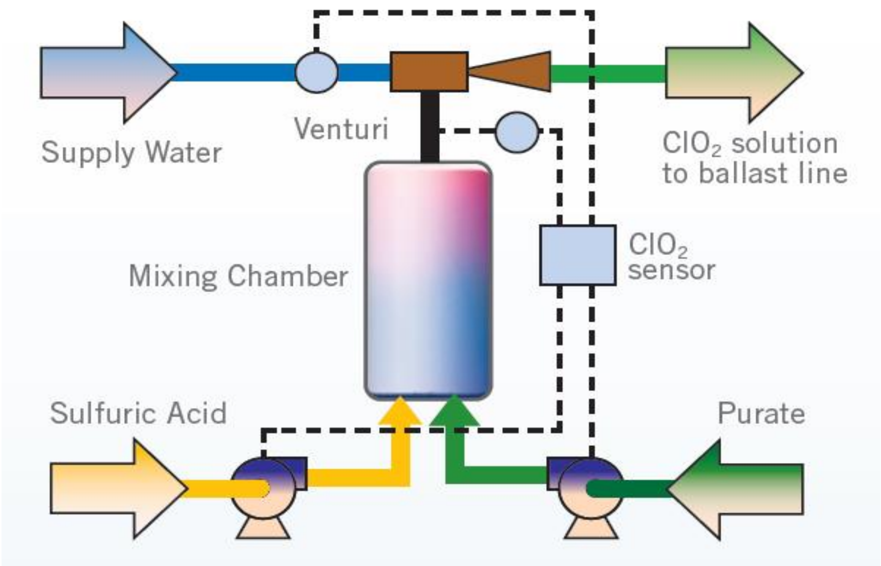

Figure 5- 4: **Typical chlorine dioxide generating process for ballast water treatment system (Ecochlor, 2015)**

Key advantage according to the vendor:

- System effectiveness is not affected by salinity, temperature, turbidity, organics, vibration or other variables that impact other treatment options.
- Alloy 20, 316L stainless steel, solvent and corrosion-resistant coatings are used for long life.
- Explosion-proof option for hazardous areas.
- The system is scaled for different sizes of ships and the space-efficient filtration system can be installed vertically or horizontally.
- Exceeds IMO D-2 regulation for ballast water treatment standards and meets proposed USCG Standards.
- Chlorine dioxide (ClO_2) technology – safe, reliable and cost-effective
- Environmentally safe – does not generate chlorine, chlorine gas or other unwanted decomposition products

System components:

1. Filter suction pump
2. Flow meter
3. Chlorine dioxide injection line
4. Supply water inlet
5. Chlorine dioxide sensor

Ballast operating sequence:

Ballasting:

1. The Treatment System generates a dilute solution of chlorine dioxide that is needed to treat incoming ballast water.
2. A small amount of supply water is needed from the ship. The water can be seawater or freshwater and is only needed during ballasting.
3. A vacuum is created in the mixing chamber as the water passes through a specially designed venturi tube. Once this vacuum is established, the two precursor chemicals are introduced into the mixing chamber.
4. The supply water then becomes a dilute solution of chlorine dioxide that is sent to the main ballast water line.

De-ballasting operation was not provided, and thus it is assumed to be proceeded as a normal de-ballasting operation after the degradation took place inside ballast tanks.

More information about BWTS3 is gathered in Table 5-6.

Table 5-6: BWTS3 parameters

BWTS3	Information by BWTS Vendor website, catalogue
Type of Treatment	Chlorine dioxide (ClO_2)
Use of chemicals	yes
Active substance use	Yes
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	up to 8400-9600 m^3/h.
Sensitivity to seawater salinity	No
Sensitivity to seawater temperature	No
Sensitivity to seawater chemical property	Not provided
Safe to ship	Not provided
Safe to crew	Not provided
Safe to environment	No risk to environment
Process time	Not provided
Power consumption	21.9 kW per 3600 m^3/h ; 9.2 kW per 1200 m^3/h
Footprint	Filtration= 6.3 m^2 + Treatment= 17 m^2 ; total= 23.3 m^2
Vendor reputation	very good
System number of components	Five components: Filter suction pump; Flow meter; Chlorine dioxide injection line; Supply water inlet ; Chlorine dioxide sensor
Type approval	Yes

5.2.3.4 Chlorination (BWTS4)

Chlorination (BWTS4) composing of the following main functional components:

1. Self-cleaning filter with 50 μm screen to remove large plankton and solid particles;
2. Electrolytic unit (including electrolytic cells and accessory dosing and degassing units) to produce sodium hypochlorite solution which is injected back into the main ballast pipe to the ballast tanks to kill the residual planktons, pathogens, larva or spores;
3. Neutralizing unit to add sodium thiosulfate solution into the treated ballast water at de-ballasting to neutralize the residual TRO; and
4. Control and auxiliary equipment.

A typical electro-chlorination ballast water treatment system is shown in Figure 5-5.

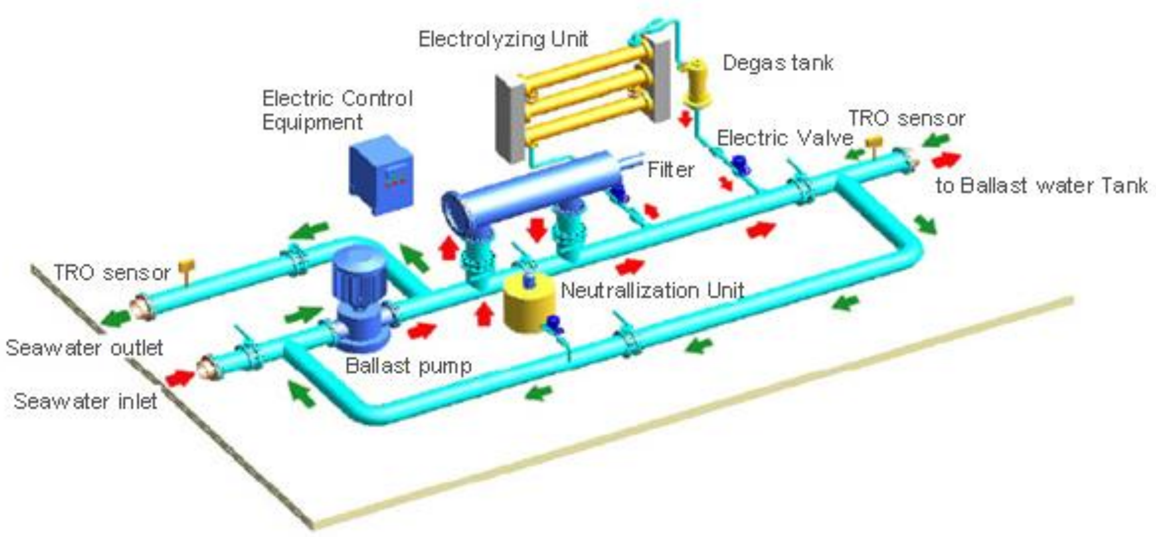

Figure 5- 5: Typical chlorination ballast water treatment system (Marineinsight, 2015)

Key advantage according to the vendor:

- Complies with IMO D-2 standard, products have type approval certified of six important classification society;
- High efficiency with low power consumption, one-step disinfection effective and complete;
- Side-stream technology with no pressure drop to main ballast pipeline, no big modification to main ballast pipeline, easy installation for new-buildings and retrofits;
- Neutralization technology which is applicable at different ship voyages;
- Modular design which is simple design for new buildings & flexible installation on retrofits;
- Treatment capacity: 100 m^3/h – 7000 m^3/h, applicable for ship types and sizes;
- Applicable to muddy water & fresh water condition;
- High performance with low operational cost & low maintenance cost;
- World-wide service network provides efficient, convenient and high standard service.

System components:

1. Filtration unit
2. Electrolysis Unit
3. Neutralization Unit

Ballast operating sequence:

Ballasting:

1. Filtration - The ballast water is filtrated by an automatic backwashing filter with 50μm screen to remove marine organisms larger than 50μm.
2. Disinfection - A small side stream of the filtered ballast water is delivered to the electrolytic unit to generate the high concentration of oxidants (mainly sodium hypochlorite solution), then the oxidants are injected back into the main ballast stream to provide effective disinfection.
3. Sodium hypochlorite solution is a very effective germicide that can be kept in ballast water for a certain period to effectively kill the plankton, spores, larvae and pathogens contained in the ballast water to meet D-2 standard.

De-ballasting:

1. Neutralization-the residual TRO level of the treated ballast water below 0.1ppm, then the treated ballast water can be directly discharged. If the residual TRO level of the treated ballast water over 0.1ppm, a neutralizer (sodium thiosulfate solution) is added into the de-ballast pipe to neutralize residual oxidants instantly.

On discharge of the treated ballast water, BWTS4 monitors the levels of TRO in ballast water. Discharge does not start until the sensors are operational and the neutralizer feed system is in operation. The neutralization system is activated with the neutralizer dose, which is calculated based on the concentration of TRO measured at the location just in front of the neutralizer injection point, to offset all TRO residuals. The sodium thiosulfate solution is injected into the suction of the ballast pump by a metering pump. Another TRO sensor is installed after the neutralizer injection point to monitor the TRO level to ensure that during discharge TRO concentration does not exceed 0.1 mg/L at any time.

More information about the BWTS4 is gathered in Table 5-7.

Table 5-7: BWTS4 parameters

BWTS4	Information by BWTS Vendor website, catalogue
Type of Treatment	Filtration + Electro-Chlorination/Electrolysis)
Use of chemicals	Yes
Active substance use	Yes
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	100-7000 m^3/h
Sensitivity to seawater salinity	Not sensitive
Sensitivity to seawater temperature	Not provided
Sensitivity to seawater chemical property	Not provided
Safe to ship	Not provided
Safe to crew	Not provided
Safe to environment	Not provided
Process time	Not provided
Power /consumption	BC-3000: 105 kW per 2701-3200 m^3/h
Footprint	• Filtration(1.575 m x 1.320 m x 3.115 m)= 6.47 m^3 • Electrolysis (2.7 m x 1.5 m x 2.914 m)= 11.8 m^3 • Neutralization, not provided total= 18.27 m^3
Vendor reputation	very good
System number of components	Three components: 1. Filtration unit 2. Electrolysis Unit 3. Neutralization Unit
Type approval	Yes

5.2.3.5 Ultraviolet (UV) irradiation (BWTS5)

UV BWTS5 is based on the use of filtration and Ultraviolet irradiation (UV) light for the efficient removal and inactivation of marine organisms Figure 5-. The UV BWTS5 does not use or generate chemicals or biocides in its treatment or cleaning processes.

The UV BWTS5 is one of a very few treatment options that does not use or generate chemicals or biocides in its treatment or cleaning process. It is based on the idea that such systems should be environmentally sound, simple, flexible and easy to install, and capable of operating on both new built and existing ships.

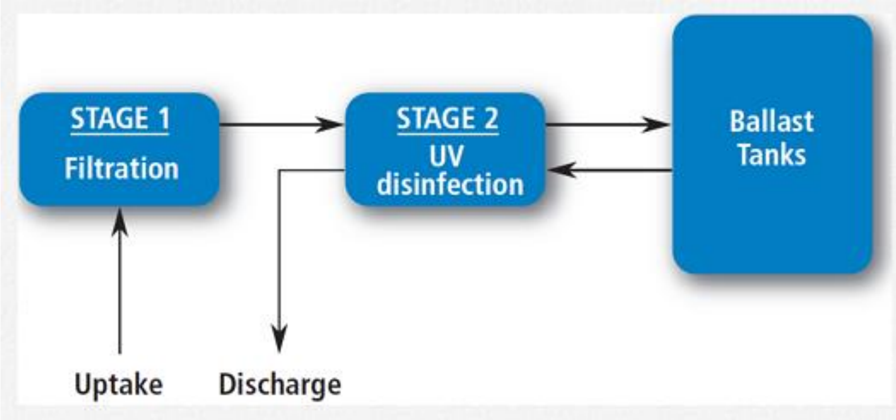

Figure 5- 6: Typical stage process of an Ultraviolet (UV) ballast water treatment system

Key advantage according to the vendor:

- The UV system was developed based on 20 years' experience of water injection on offshore platforms, water treatment for fish farming and drinking water plants in Norway.
- High power UV for the efficient killing or inactivation of organisms, bacteria and pathogens in ballast water.
- One UV lamp per chamber (167 m^3/h flow rate per chamber).
- Standardized UV chamber, installed in parallel on a single manifold for higher flows.
- Developed and manufactured for installation aboard ships.
- Optimized for minimum maintenance and ease of operation.
- It is self-cleaning, with no moving parts or need for chemical cleaning.
- UV and temperature sensor in each chamber.
- The system is easy to install on board existing ships (retrofit) as well as on new built ones.
- The system can be delivered as a complete skid or as a customized solution.
- It accommodates a wide range of ballast water capacities and can handle flows up to 3000 m^3/h (or higher upon request).
- The system has fewer parts and UV lamps in comparison with similar systems.
- The system will automatically optimize the power consumption pending UV intensity which is based on the water quality during ballasting (turbidity, etc). The system's extensive treatment capacity has shown that it is capable of meeting the more stringent California standard.

System components:

1. UV system
2. Filters: BWTS5 offers three different (40 micron) filters: B&K (candle type) FilterSafe (basket type) Filtrex (basket type). All three filter types have automatic back flushing and are self-cleaning.
3. Control system: The ballast control system allows easy operation of the UV BWTS5

Ballast operating sequence:

Ballasting:

1. The ballast water flows through system proprietary 40 micron filter. The filter removes larger organisms and particles and back flushes them overboard at the ballasting location.
2. After passing the filter, the ballast water continues through the UV chambers on its way to the ballast tanks. The UV light kills or inactivates organisms, viruses and bacteria in the ballast water.

De-ballasting:

1. The filter is automatically bypassed during de-ballasting, and
2. The ballast water receives a second UV-treatment during discharge as a safeguard to ensure compliance.

Maintenance:

- Few movable parts which requires little or no system maintenance and ensures operational reliability.
- The system has fewer parts and UV lamps in comparison with similar systems.
- The patented UV chamber in CuNi, the high water flow and high UV intensity make the UV lamps and the internals of the UV chamber self-cleaning and ensure a relative long service life.
- A self-cleaning UV system combined with the automatic back-flushing filters results in a minimum requirement for system cleaning and maintenance for the ship's crew.

More information about the UV BWTS5 is gathered in Table 5-8.

Table 5-8: BWTS5 parameters

BWTS5	Information by BWTS Vendor website, catalogue
Type of Treatment	Filtration + Ultraviolet irradiation
Use of chemicals	No chemicals
Active substance use	yes
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	up to 3000 m^3/h
Sensitivity to seawater salinity	Not sensitive
Sensitivity to seawater temperature	Not sensitive
Sensitivity to seawater chemical property	Not sensitive
Safe to ship	No risk to ship nor does it influence corrosion in ballast water system
Safe to crew	No risk to crew
Safe to environment	No risk to environment
Process time	Not provided
Power consumption	360 kW per 3000 m^3/h
Footprint	Filter (2.3 m^2)+ UV manifold (3.5 m^2) (18 champers)+ power panel (8.1 m^2)= 13.9 m^2
Vendor reputation	very good
System number of components	three components: UV system; filters; control system
Type approval	Yes

5.3.3.6 Ultraviolet (UV) irradiation (BWTS6)

BWTS6 is based on filtration and Ultraviolet irradiation (UV) light that doesn’t use active substances. During ballasting, water is processed through the filter to remove any particles or organisms larger than 50 microns in size. It then passes through the UV treatment and to the ship’s ballast system. Back-flushing water is returned over board at the ballasting site. During de-ballasting, the filter is bypassed and the ballast water receives a second dose of ultraviolet light before being discharged overboard.

UV dosage results from a combination of lamp power, flow path, and exposure time. The flow characteristics through the UV chamber are optimized to make best use of the UV power provided.

Key advantage according to vendor:

- Automatic operation with very little crew attention;

- Effective - not affected by water salinity, temperature, or hold time in the ballast tank;
- 100% safe without side effects;
- Organisms cannot build resistance against UV;
- No increased corrosion risk as with chemical oxidants;
- No transportation, storage, or handling of chemicals;
- No danger of overdosing or release of residual disinfectants;
- No harmful toxic or significant nontoxic disinfection by-products;
- The system was in the first group of companies to receive Alternative Management System (AMS) approval from the U.S. Coast Guard (USCG) on April 15, 2013 for its BWTS;
- The BWTS was among the first to receive IMO Type Approval from Lloyd's Register on behalf of the U.K. Maritime and Coast Guard Agency (MCA) in April 2009.

System components:

1. Control & Power Panels
2. Compact Filter: (30-40 micron)
3. UV Treatment Chamber & Central Outlet.

Ballast operating sequence:

Ballasting:

1. The ballast water flows through 30-40 micron filter. The filter removes larger organisms and particles and back flushes them overboard at the ballasting location.
2. After passing the filter, the ballast water continues through the UV chambers on its way to the ballast tanks. The UV light kills or inactivates organisms, viruses and bacteria in the ballast water.

De-ballasting:

1. The filter is automatically bypassed during de-ballasting, and
2. The ballast water receives a second UV-treatment during discharge as a safeguard to ensure compliance.

Maintenance:

- The UV lamps have an expected service life of 5,000+ operating hours which allows for hundreds of typical ballasting cycles.

- BWTS6 systems in service for over 10 years have not experienced issues with lamp failure or breakage.
- The system employs an automatic wiping mechanism to keep deposits from accumulating on the sleeves.
- Each UV reactor contains a temperature sensor, a UV intensity sensor, and a drain.
- The reactor chamber has an inspection and access hatch for routine checks and maintenance of reactor internals.
- Recent improvements include the addition of UV reactor level and moisture sensors for increased safety and relocation of the UV cooling valve to the top of the UV reactor chamber for improved air removal.

More information about the BWTS6 is gathered in Table 5-9.

Table 5-9: BWTS6 parameters

BWTS6	Information by BWTS Vendor website, catalogue
Type of Treatment	Filtration + Ultraviolet
Use of chemicals	No chemicals
Active substance use	yes
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	up to 60-6000 m^3/h.
Sensitivity to seawater salinity	Not sensitive
Sensitivity to seawater temperature	Not sensitive
Sensitivity to seawater chemical property	Not sensitive
Safe to ship	No risk to ship nor does it influence corrosion in ballast water system
Safe to crew	No risk to crew
Safe to environment	No risk to environment
Process time	
Power/consumption	228 kW per 3000 m^3/h or 75 kW per 1000 m^3/h (may add 15-30 kW if backwash pump is used)
Footprint	• Filter in meters (1.44 m x 1.6 m x 2.385 m) =5.49 m^3 • UV in meters (1.11 m x 0.63 m x 0.860 m)=0.601 m^3 • Power panel in meters (1.800 m x 0.800 m x 1.800 m) x2= 5.184 m^3 • Control cabinet in meters (0.600 m x 0.21 m x 0.760 m)= 0.095 m^3 • total footprint of five components= 11.37 m^3
Vendor reputation	very good
System number of components	three components: 1. Control cabinet. 2. Power panel. 3. Filter unit: (30-40 micron). 4. UV unit (medium pressure).
Type approval	Yes

5.3.3.7 Ultraviolet (UV) irradiation (BWTS7)

BWTS7 is a modular BWTS which operates in-line during the uptake of ballast water. The first stage is a filter that was specially designed for ballast water applications. It significantly reduces the sediment load from the ballast water and also removes some of the micro-organisms. The filter is installed on the discharge side of the ballast water pumps and is fully automatic in terms of its operation and cleaning without affecting the filtration process, and flushing water is returned into seawater. The UV unit employs high-intensity, medium-pressure ultraviolet (MPUV) lamps to destroy living micro-organisms present in the liquid being treated. During de-ballasting, the filter unit is by-passed. The ballast water is treated again by the UV unit only to destroy any organisms which might have regrown in the tanks during the voyage.

Key advantage according to vendor:

- Effective disinfection of harmful aquatic organism
- Component concept for stabilized capacity expansion
- Less power consumption
- Low maintenance cost
- Simple operating system
- Automatic back flushing in the filtration unit
- Automatic wiper cleaning in the UV unit
- Easy installation - skid / vertical, horizontal arrangement, separate components
- Irrespective of water condition such as water salinity, temperature
- No requirement of dosing liquid or powder chemicals for disinfection
- Not producing active substance

System components:

1. Control panel & UV Power Supply Panel
2. Filter unit : (50 micron): (choose between Original + MEGA unit)
3. UV unit (medium pressure): (choose between Original or MEGA).

Ballast operating sequence:

Ballasting:

1. When ballasting mode starts, the ballast water from sea chest enters through the inlet pipe into the filter and flows through the cylindrical filter element from inside out. Organisms larger than 50μm are eliminated and those smaller than 50μm will pass into UV unit for disinfection.
2. During filtration, sediments are accumulated on the surface of the filter element and flushed out to overboard by the back flushing function without any disturbance on filter operation.

De-ballasting:

1. During de-ballasting mode, the ballast water from the ballast tanks passes through the UV unit to prevent reproduction of organisms and flows out to overboard.
2. During bypass mode, the ballast water skips filter and UV unit and simply flows out to overboard.

More information about the BWTS7 is gathered in Table 5-10.

Table 5-10: BWTS7 parameters

BWTS7	Information by BWTS Vendor website, catalogue
Type of Treatment	Filtration + Ultraviolet irradiation with medium-pressure ultraviolet (MPUV) lamps
Use of chemicals	No chemicals
Active substance use	Yes
Capital cost	Not provided
Operating cost	Not provided
Maintenance cost	Not provided
System Ballast Capacity	up to 800-3000 m^3/h.
Sensitivity to seawater salinity	Not sensitive
Sensitivity to seawater temperature	Not sensitive
Sensitivity to seawater chemical property	Not sensitive
Safe to ship	No risk to ship nor does it influence corrosion in ballast water system
Safe to crew	No risk to crew
Safe to environment	No risk to environment
Process time	
Power consumption	210 kW per 3000 m^3/h or 70 kW per 1000 m^3/h
Footprint	9.83 m^2
Vendor reputation	very good
Type approval	Yes

5.2.4 Acquiring missing data flowchart

In order to make sure that missing information between systems are not influencing the selection of the model. A schematic flowchart of how the missing data aggregation and evaluation is presented Figure 5-2.

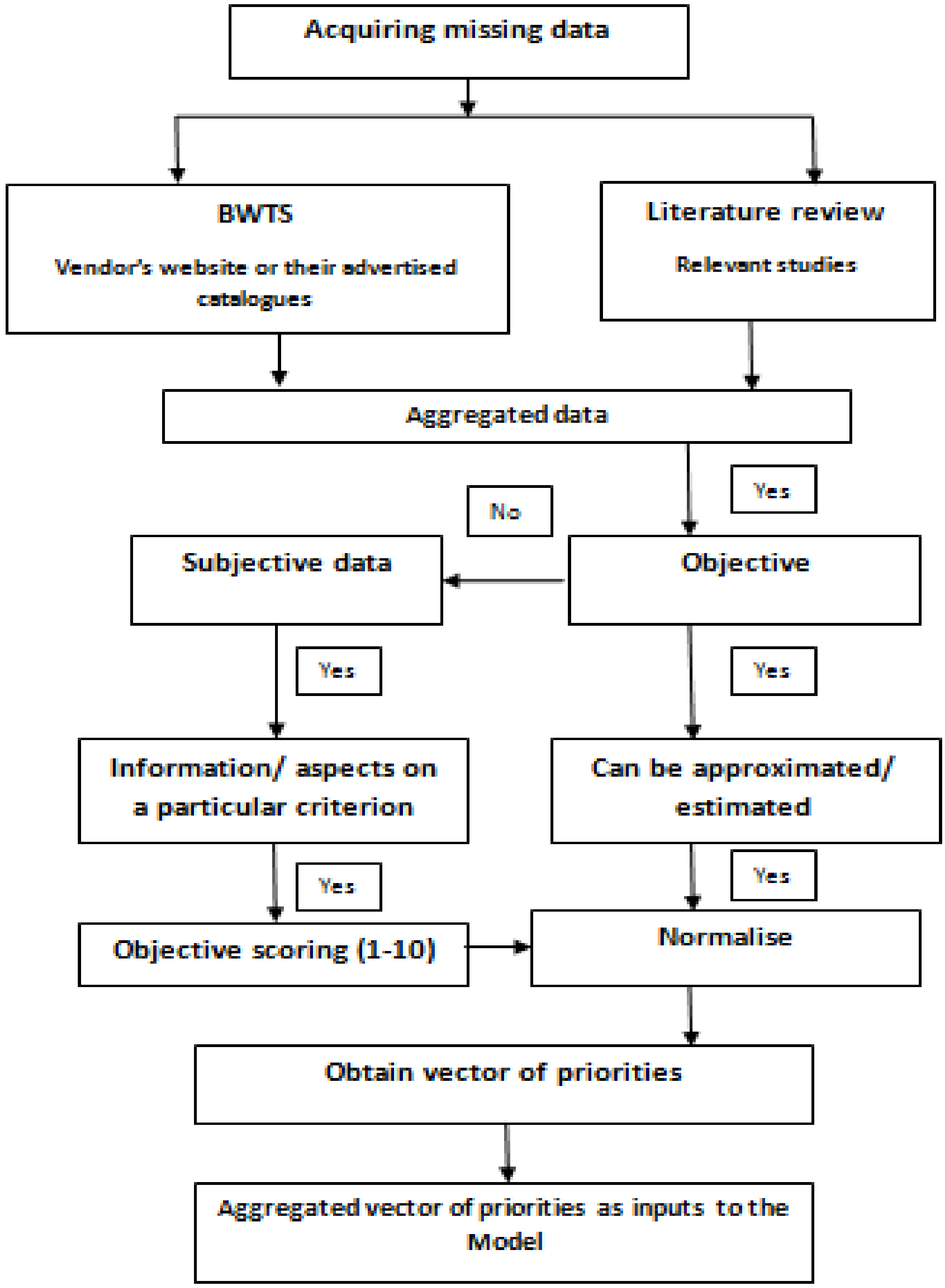

Figure 5-7: Acquiring missing data flowchart

To summarise the steps used in Figure 5-2 for acquiring and evaluating the missing information in this study are as follow:

- Firstly, the data related to each BWTS alternative was acquired from the BWTS advertised website and catalogues. If the information needed is missing to evaluate a particular criteria or criterion, it will be acquired from the literature review.
- Secondly, if the collected information were objective (tangible) then they were processed according to their type for better approximation or estimation. After that, all objective data are normalised to form the AHP vector of priorities as inputs to the model. If there is no objective information found, the subjective (intangible) information and aspects of a particular criterion or criteria will be aggregated instead.
- Thirdly, based on the intuitive understanding of the aggregated information of a particular criterion or criteria an evaluation score (1-10) is properly assigned accordingly to the alternative with regards to that particular criterion. It is worth noting that in a particular criterion, 10 could indicate the worse score and thus not satisfying that criterion whilst for another it may indicate the best score depending on each particular criterion.
- Finally, scores for each particular alternative are normalised for the AHP vector of priorities as inputs to the model.

Vector of priorities should be checked for inconsistency before adding them as inputs to the model. The aggregation and evaluation of the missing information are presented and discussed next.

5.2.4 .1 Cost

5.2.4.1.1 Minimum Capital & Operating Costs

In this study, capital cost includes purchasing and installing of a BWTS. Whilst the operating cost is the operation of a BWTS which also depends on its power requirement, maintenance costs associated with the routine & preventive actions for repairs, cleaning, replacing items etc. It is obvious that minimising the cost can be accomplished by minimising both capital and operating costs which are highly demanded by any organisation such as a shipping company. This was also shown by the aggregated evaluation results obtained from the expert’s interview in chapter 4.

Unfortunately, these costs are one of the very hard types of data to obtain from a BWTS vendors. Costs are always treated as very confidential information by BWTS vendors. Therefore, and due to the lack of response by the BWTS vendors to provide such information, the required data were acquired from extensive literature review in order to help gathering such information to the developed model as shown in Table 5-11. Although such information cannot be very accurate or precise but it provides a reasonable value to enable the evaluation between the BWTS alternatives.

In Table 5-11 the approximated capital and operating cost was collected from relevant literature review. It is worth nothing that there are large differences between the given estimates. Therefore, taking the *median average value* (in red) is found more proper to be used as it provides more accurate estimates than a mean average value because of the large variation between the given approximations acquired from the literature (UCL, 2010). In order to check the model for the extreme price change, the highest cost and lowest cost will also be examined for the sensitivity to prices.

Table 5-11: List of approximation of the capital and operating cost per type of disinfection method; red numbers represents the median value; annual values were omitted as it has represented particular case only.(Source collected from (Gregg et al., 2009, Jing et al., 2012, Blanco-Davis and Zhou, 2014, Berntzen, 2010, King et al., 2009, King et al., 2012))

Disinfection method	Approximate Capital Cost	Approximate Operating Cost	References
Ultraviolet irradiation treatment (UV)	• $300,000-400,000 • $3-4 million • $1.000 million • $180,000 • $155,000 • $1 million • $930,000-1 million	• $0.065-0.26 per tonnes of BW • $22,750 annual operating cost • $10 per 1000 m^3 • $0.11 per tonnes BW (median) • $11,000 annual for VLCC	• Gregg et al 2009 • Jing et al (2012) • Blanco-Davis and Zhou (2014) • Berntzen (2010) • King et al (2009) • King et al (2012)
Chlorine	• $160,000- 400,000 • $160,000 • $1 million • $940,000 • 670,000	• $0.32 per tonnes of BW	• Gregg et al 2009 • Jing et al (2012) • King et al (2009) • King et al (2012)
Chlorine dioxide	• $260,000-400,000 • $260,000-400,000 • 250,000	• $0.06 per tonnes of BW	• Gregg et al 2009 • Jing et al (2012)
Ozone treatment	• $800,000-1.6 million • 1-1.6 million • 1 million	• $0.28-0.32 per tonnes of BW • $0.3 per tonnes of BW	• Gregg et al 2009 • Jing et al (2012) • Berntzen (2010)
Electro-chlorination	• $500,000 • $150,000 • $750,000 • $660,000 • 580,000	• $0.02 per tonnes of BW • $200 annual • $ 0.11 per tonnes of BW • $0.15 per tonnes of BW	• Gregg et al 2009 • King et al (2009) • King et al (2012)
De-Oxygenation	• $150,000-400,000 • $150,000-400,000 • $800,000 • $730,000 • $565,000	• $0.05 per tonnes of BW • $ 0.32 per tonnes of BW • $0.27 per tonnes of BW	• Gregg et al 2009 • Jing et al (2012) • Blanco-Davis and Zhou (2014) • King et al (2009) • King et al (2012)

Based on the collected information in Table 5-11; the calculated average median value of both the capital and the operating costs are presented in Table 5-12.

Table 5-12: The identified median capital and operating costs of each BWTS disinfection alternative

Disinfection method	Capital Cost	Operating cost per tonnes of BW
Ultraviolet irradiation (UV)	• $930,000	• $0.11
Chlorine	• $400,000	• $0.32
Chlorine dioxide	• $250,000	• $0.06
Ozone treatment	• 1 million	• $0.30
Electro-chlorination	• $580,000	• $0.15
De-Oxygenation	• $565,000	• $0.27

In order to account for life cycle usage phase, the life of the ship has been assumed to be that of 20 years and the treatment for 600,000 tonnes of ballast water a year. This means that all BWTS alternatives are assumed to last for the full 20 years, and their operating cost is estimated according to the collected data from the literature for treating 600,000 tonnes of ballast water per year. It was also assumed a 6% discount rate per annum, but just to check the latter assumption, 8% and 12% will also be checked for their sensitivity on the output in chapter 7.

The present value (PV) was obtained by using equation (5-1) (HSE, 2002):

$$PV = C_o + C_k(1-(1+r)^{-L})/r \qquad (5\text{-}1)$$

"PV" is present value; *"r"* is the discount rate per year; *"L"* is the projected life in years; "C_o" is the initial capital cost; "C_k" is the cost in year *K* (for *K*=1 to *L*).

Using the information acquired in the Table 5-12, the PV and operating cost information required for the model are obtained as shown in the Table 5-13.

Table 5-13: Estimated present value (PV) of each type of disinfection method, for 20 years and 600,000 tonnes of ballast water treatment per year

Disinfection method	Present value (PV)	Operating cost per 600,000 tonnes BW
Ultraviolet irradiation treatment (UV)	$ 1,687,014.00	$ 66,000.00
Chlorine treatment	$ 2,602,224.00	$ 192,000.00
Chlorine dioxide	$ 662,917.00	$ 36,000.00
Ozone treatment	$ 3,064,585.00	$ 180,000.00
Electro-chlorination	$ 1,612,292.00	$ 90,000.00
De-Oxygenation	$ 2,423,127.00	$162,000.00

The operating cost per tonnes of ballast water shown in Table 5-13 is assumed constant for the lifespan of the ship i.e., 20 years. The values obtained from Table 5-13 are re-arranged and used to represent the BWTS alternatives PV costs according to their disinfection method used and donated from BWTS1 to BWTS7 respectively as shown in Table 5-14.

Table 5-14: Listed seven BWTS alternatives according to their disinfection methods, obtained PV capital cost values, and denoted from BWTS1 up to BWTS7 respectively.

BWTS disinfection method	Denoted	PV
De-Oxygenation	BWTS1	$2,423,127.00
Ozone treatment	BWTS2	$3,064,585.00
Chlorine dioxide treatment	BWTS3	$662,917.00
Chlorine treatment	BWTS4	$2,602,224.00
Ultraviolet irradiation treatment (UV)	BWTS5	$1,687,014.00
Ultraviolet irradiation treatment (UV)	BWTS6	$1,687,014.00
Ultraviolet irradiation treatment (UV)	BWTS7	$1,687,014.00

Based on the calculated PV costs, Table 5-14, the data are normalised and the vector of priority is obtained as shown in Table 5-15.

Table 5-15: Listed priorities between the given BWTS alternatives of the minimum capital cost

BWTS disinfection method	denoted	Vector of priority of the minimum capital cost
De-Oxygenation	BWTS1	0.094
Ozone treatment	BWTS2	0.074
Chlorine dioxide treatment	BWTS3	0.342
Chlorine treatment	BWTS4	0.087
Ultraviolet irradiation treatment (UV)	BWTS5	0.134
Ultraviolet irradiation treatment (UV)	BWTS6	0.134
Ultraviolet irradiation treatment (UV)	BWTS7	0.134

It should be mentioned that the approximated PV capital cost and operating cost may not represent the real cost of the alternatives. However, due to the lack of information and rejection of supports by the BWTS vendor to provide such information, acquiring information from the literature review was the only appropriate approach. This had given the three UV treatments the same capital cost and thus it may be inconsistent in real world.

The result obtained from the pairwise comparisons, as shown in Table 5-15, BWTS3 (0.342) was selected as the most capital cost effective alternative amongst the given alternatives which satisfied *the minimum capital cost* criterion which used in the model.

Again due to the missing information about the precise capital cost may influence this result as each BWTS alternative was evaluated according to its disinfection method found in the literature review.

The calculated operating cost for each BWTS to treat 600,000 tonnes of ballast water per year is shown in Table 5-16.

Table 5-16: Listed seven BWTS alternatives according to their disinfection methods, operating costs values and denoted from BWTS1 up to BWTS7 respectively.

BWTS disinfection method	Denoted	Operating cost for 600,000 tonnes per year ($)
De-Oxygenation	BWTS1	**162,000.00**
Ozone treatment	BWTS2	**180,000.00**
Chlorine dioxide treatment	BWTS3	**36,000.00**
Chlorine treatment	BWTS4	**192,000.00**
Ultraviolet irradiation treatment (UV)	BWTS5	**66,000.00**
Ultraviolet irradiation treatment (UV)	BWTS6	**66,000.00**
Ultraviolet irradiation treatment (UV)	BWTS7	**66,000.00**

The priority vector of the matrix obtained is shown in Table 5-17.

Table 5-17: Listed priorities between the given BWTS alternatives for the minimum operating cost

BWTS disinfection method	denoted	Vector of priority for the minimum operating cost
De-Oxygenation	BWTS1	0.068
Ozone treatment	BWTS2	0.062
Chlorine dioxide treatment	BWTS3	0.308
Chlorine treatment	BWTS4	0.058
Ultraviolet irradiation treatment (UV)	BWTS5	0.168
Ultraviolet irradiation treatment (UV)	BWTS6	0.168
Ultraviolet irradiation treatment (UV)	BWTS7	0.168

The result obtained from the pairwise comparisons, Table 5-17, the BWTS3 (0.308) was selected as the most operating cost effective alternative amongst the given alternatives. This is because BWTS3 alternative satisfied or scored more than other alternatives toward the *minimum operating cost* criterion. This result is based on evaluations of each BWTS alternative according to its disinfection method found in the literature.

5.2.4.1.2 Minimum maintenance cost

Maintenance cost is part of the operating cost of the BWTS, but here it is the cost associated with the routine & preventive actions for repairs, cleaning, replacing an item(s) in the given BWTS. Maintenance issue is another big area which needs to be considered in more details for future studies.

It is very difficult to accurately estimate the maintenance costs particularly that it depends on many parameters i.e. direct or indirect, controlled or uncontrolled and also on the way how each system is chosen to be maintained by the operator i.e. routine & preventive maintenance. Therefore, because of the lack of objective data about each BWTS' maintenance expenses, comparisons between the alternatives are considered subjectively based on the provided information of each treatment system as shown in Table 5-18. Fortunately, one of the advantages of the AHP as MCDM method is that it can use both tangible data like price or weight which can be measured and intangible data such as safety.

In Table 5-18 the subjective maintenance aspects noted for each of the given BWTS alternatives are based on the information provided for each BWTS vendor. It is important to note that, the subjective information were evaluated by giving them a score from 1 to 10, where 10 or 'high' represents the *worst* score that satisfies this particular criterion which is *minimum maintenance cost* for each of the given BWTS alternative as shown and summarised in Table 5-18. On the other hand, low scores represent the lowest costs and thus *better* scores that satisfies the *minimum maintenance cost* criterion.

Table 5-18: Subjective maintenance cost and ease of maintenance comparison between the given BWTS; a rank from 1 to 10, where 10 represents the worst score that satisfy this particular criterion which is minimum maintenance cost.

BWTS	BWTS disinfection method	Maintenance aspects	Subjective –minimum maintenance cost (1-10)
1	De-Oxygenation	• Protects ballast water tank coatings, sacrificial anodes and steel structure against the effect of corrosion. • Reduces the cost of coating maintenance. • Reduces corrosion up to 84% lower corrosion. • No filters, so no replacement or cleaning needed. • Venture injectors, does not have moving part and thus maintenance is low. • SGG may require maintenance but not much information is available. • No storage is required or topping up for the system. • Crew training is required to carry out maintenance on the SSG and system in case of fault.	• **Low (2)**
2	Ozone treatment	• System consists of two generators i.e. ozone and oxygen, but no information of maintenance provided. • Pumps in the system may require maintenance at a certain intervals. • No storage is required or topping up for the system. • Crew training is required to carry out maintenance on the generators and system in case of fault.	• **Medium (5)**
3	Chlorine dioxide treatment	• System requires generating dilute solution of CLO_2 and supplying water which requires crew training to keep system maintained in case of fault. • Venture tube does not require maintenance. • Filter will require cleaning and/or replacement at certain intervals. • Storage is required topping up for the dilution system. • Pumps in the system may require maintenance at a certain intervals • Crew training & expertise of how the system works is required to carry out maintenance correctly and effectively in case of fault	• **High (8)**
4	Chlorine treatment	• Filter will require cleaning and/or replacement at certain intervals. • Scarce information on maintenance for the electrolysis units. • Crew training & expertise of how the system works is required to carry out maintenance correctly and effectively in case of fault. • No storage is required or topping up for the system. • Checking TRO and neutralizer solution requires more training for crew.	• **Low (2)**

5	Ultraviolet irradiation treatment (UV)	• Filter will require cleaning and/or replacement at certain intervals. • UV Lamp replacement after 3000 hours of operations or breakage • Adjustment to the UV transmittance and sensors check. • Self-cleaning mechanism increase the low maintenance requirement. • No storage is required or topping up for the system.	• **Low (2)**
6	Ultraviolet irradiation treatment (UV)	• Filter will require cleaning and/or replacement at certain intervals. • UV Lamp replacement after 5000 hours of operations or breakage • An automatic wiping mechanism increases the low maintenance requirement. • No storage is required or topping up for the system.	• **Low (2)**
7	Ultraviolet irradiation treatment (UV)	• Filter will require cleaning and/or replacement at certain intervals. • UV Lamp (medium pressure) replacement after hours of operations or breakage • An automatic wiping mechanism increases the low maintenance requirement. • No storage is required or topping up for the system.	• **Low (2)**

In a short example of how Table 5-18 evaluated the alternatives when comparing between two BWTS alternatives such as UV and ozone treatments. This was done based on the subjective information as noted in the maintenance aspects. For example, the ozone BWTS consisted of two generators i.e., ozone and oxygen, pumps which may require particular type of maintenance and also this treatment have potential for crew training requirement on maintaining this type of BWTS and thus was scored higher than UV. On the other hand, the UV alternative, requires cleaning and replacement of the UV lamps after 3000 or 5000 hours which is considered relatively low type of maintenance, thus scoring lower than ozone. The same evaluation method were used with the rest of the BWTS alternatives.

Based on the subjective information and the objective scoring (1-10) of the maintenance costs, Table 5-18, the pairwise comparison matrix Table 5-19 is obtained. The priority vector of the less expensive maintenance cost alternative through the pairwise comparisons was carried out in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is 0.00 which is consistent.

Table 5-19: The AHP judgment matrix obtained of the maintenance cost criterion for each of the given BWTS alternatives

Minimum maintenance cost	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	2.50	4.00	1.00	1.00	1.00	1.00
BWTS2	0.40	1.00	1.60	0.40	0.40	0.40	0.40
BWTS3	0.25	0.63	1.00	0.25	0.25	0.25	0.25
BWTS4	1.00	2.50	4.00	1.00	1.00	1.00	1.00
BWTS5	1.00	2.50	4.00	1.00	1.00	1.000	1.000
BWTS6	1.00	2.50	4.00	1.00	1.00	1.00	1.000
BWTS7	1.00	2.50	4.00	1.00	1.00	1.00	1.00

λ max = 7.00, Consistency Index CI = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the matrix obtained is shown in Table 5-20.

Table 5-20: Listed priorities between the given BWTS alternatives for the minimum maintenance cost

BWTS Disinfection method	Denoted	Vector of priority for the minimum maintenance cost
De-Oxygenation	BWTS1	0.177
Ozone treatment	BWTS2	0.071
Chlorine dioxide treatment	BWTS3	0.044
Chlorine treatment	BWTS4	0.177
Ultraviolet irradiation treatment (UV)	BWTS5	0.177
Ultraviolet irradiation treatment (UV)	BWTS6	0.177
Ultraviolet irradiation treatment (UV)	BWTS7	0.177

The result obtained from the pairwise comparisons, Table 5-20, the BWTS2 (0.071) and BWTS3 (0.044) treatments were shown as the least preferred alternatives for satisfying the minimum maintenance cost.

Due to the missing information, it should be noted that the subjective evaluations may influence the accuracy of these results because they are based on subjective evaluation and objective scoring (1-10) of each BWTS alternative according to the aggregated information from each BWTS vendor.

5.2.4.2 Safety

Safety is an important role of being free of danger or risks. In this study, the safety of a BWTS for a given ship can be indicated by maximising three aspects:

- Maximising environmental safety i.e. risks to living environment when discharged;
- Maximising ship safety e.g. corrosion to ballast tanks or hazardous to explosive space;
- Maximising crew safety e.g. crew health.

The environmental safety is meant to be that the treated ballast water must not cause threat or pollution or having any negative impacts to the receiving waters and must meet the environmental regulations. Ship safety, is meant to consider all the aspects that may cause threat to ship structure, systems etc. Finally, crew safety is meant to consider risks that may cause threat to the crew health and safety.

Due to the lack of objective information to assess the safety of each BWTS alternative, the subjective data of each type of treatment was acquired from the literature according to their disinfection method in order to subjectively compare the safety risk aspects between the given BWTS alternatives as shown in Table 5-21.

It is important to note that, in Table 5-21, subjective safety aspects were noted for each of the given disinfection method are based on the information acquired from the relevant literature review. After collecting the subjective information from the literature, a score from 1 to 10, where 10 represents the *worst* or highest risk towards the criteria which are *maximising the environmental*, *ship* and *crew* were obtained for each of the given BWTS alternative, as shown in Table 5-21. On the other hand, lower scores represent low risks, thus they are better to satisfy the *safety* criterion by its sub-criteria.

Table 5-21: Subjective risk to environment, ship and crew comparison between the given disinfection methods; a rank from 1 to 10, where 10 represents the highest risk rank to the objective or criterion which is maximum environment, ship and crew.

Disinfection method	Safety aspects	Subjective environmental safety risk (1-10)	Subjective ship safety risk (1-10)	Subjective crew safety risk (1-10)	References
Ozonation	• Environmentally friendly • Risks of biocide on discharge • Risks of irritation to eyes and lungs. • Risks of increasing corrosion rate in ballast tanks. • Reacts with water and produce human carcinogen by-product known as bromate.	• Medium (5)	• Medium (5)	• Medium (5)	• (Gregg et al., 2009) • (Gottschalk et al., 2009) • (Sassi et al., 2005)(• (Herwig et al., 2006) • (von Gunten, 2003a) • (Von Gunten, 2003b) • (Wright et al., 2010) • (Oemcke and Van Leeuwen, 2005a) • (Jing et al., 2012)
Ultraviolet (UV) irradiation	• Environmentally friendly. • No by-products risks. • Genetically muted species in discharge. • Release of mercury from UV lamps. • Low corrosion to ballast water tanks	• Low (2)	• Low (2)	• Low (2)	• (Gregg et al., 2009) • (Severin et al., 1983) • (Jing et al., 2012) • (Sutherland et al., 2001) • (Xu et al., 2011) • (Sassi et al., 2005)
De-oxygenation	• Environmentally friendly • Would not pose a toxic risk to natural receiving waters. • Low corrosion to ballast water tanks	• Low (2)	• Very low (1)	• Low (3)	• (Tamburri et al., 2002) • (McCollin et al., 2007b) • (Jing et al., 2012) • (de Lafontaine et al., 2013) • (de Lafontaine and Despatie, 2014)
Chlorination	• Chlorinated seawater accelerated the corrosion rate in pipeline and ballast tanks. • Reacts with water and produce human carcinogen by-product known as bromate. • Residual chlorine may pose an environmental risk. • Recommended the use of a reduction agent before discharge.	• Medium (5)	• Medium (5)	• Low (3)	• (Song et al., 2009) • (Carney, 2011) • (Gregg et al., 2009) • (Tsolaki et al., 2010) • (Matousek et al., 2006)

	• Many by products and residual is similar compounds to ozonation.				
Chlorine Dioxide	• Environmentally friendly, no by-products production. • Production of noxious gas likely to pose health risks to crew due to the use of hydrochloric acid as an activator. • No increase corrosion found to be difference from seawater on metal up to 10 mgL^{-1}. • Safe to discharge for concentration less than or equal 200 mgL^{-1}.	• Low (3)	• Low (3)	• Medium (5)	• (Gregg and Hallegraeff, 2007) • (Maranda et al., 2013) • (Gregg et al., 2009)

5.2.4.2.1 Maximum environmental safety

The evaluation between two disinfection methods e.g. UV and ozone are based on the identified safety aspect between the two treatment systems. For example, the ozone treatment was noted with risks of pumping out by-products and risks to human health, thus this treatment was evaluated to have more potential risks than other alternative such as UV. On the other hand, the UV treatment, had no risks to discharging by products, but noted with risks of releasing mercury from UV lamps in breakage which is considered relatively lower risks to the environment safety. The same evaluation method was used with the rest of the BWTS alternatives.

The subjective evaluations and the objective risks scoring (1-10) in Table 5-21 of the environmental safety risk are summarised in Table 5-22, then the pairwise comparisons matrix Table 5-23 are obtained.

Table 5-22: Listed seven BWTS alternatives from BWTS1 to BWTS7, their disinfection method, their subjective assessment for their environmental safety risk, and their environmental risk ranked (1-10) according to the information in Table 5-21.

BWTS disinfection method	Denoted	Subjective environmental safety risk	Environmental safety risk score (1-10)
De-Oxygenation	BWTS1	Low	2
Ozone treatment	BWTS2	Medium	5
Chlorine dioxide treatment	BWTS3	Low	3
Chlorine treatment	BWTS4	Medium	5
Ultraviolet irradiation treatment (UV)	BWTS5	Low	2
Ultraviolet irradiation treatment (UV)	BWTS6	Low	2
Ultraviolet irradiation treatment (UV)	BWTS7	Low	2

Table 5-23: The AHP judgment matrix obtained of the maximum environmental safety criterion for each of the given BWTS alternatives

Maximum environmental safety	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	2.50	1.50	2.50	1.00	1.00	1.00
BWTS2	0.40	1.00	0.60	1.00	0.40	0.40	0.40
BWTS3	0.67	1.67	1.00	1.67	0.67	0.67	0.67
BWTS4	0.40	1.00	0.60	1.00	0.40	0.40	0.40
BWTS5	1.00	2.50	1.50	2.50	1.00	1.000	1.000
BWTS6	1.00	2.50	1.50	2.50	1.00	1.00	1.000
BWTS7	1.00	2.50	1.50	2.50	1.00	1.00	1.00

λ max = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less environmentally risky alternative through the pairwise comparisons was carried out in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is calculated as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-24.

Table 5-24: Listed priorities between the given BWTS alternatives for the maximum environmental safety

BWTS disinfection method	Denoted	Vector of priority for the Maximum environmental safety
De-Oxygenation	BWTS1	0.183
Ozone treatment	BWTS2	0.073
Chlorine dioxide treatment	BWTS3	0.122
Chlorine treatment	BWTS4	0.073
Ultraviolet irradiation treatment (UV)	BWTS5	0.183
Ultraviolet irradiation treatment (UV)	BWTS6	0.183
Ultraviolet irradiation treatment (UV)	BWTS7	0.183

The result obtained from the pairwise comparisons, Table 5-24, the BWTS2 (0.073) and BWTS4 (0.073) treatments were shown as the least preferred alternatives for satisfying the *maximum environmental safety* criterion.

It should be noted that due to the missing information, subjective assessment, result obtained may influence this result because it is based on subjective evaluation and scoring risks (1-10) of each BWTS alternative according to the provided information from the literature review.

5.2.4.2.2 Maximum Ship Safety

Based on the subjective information and the objective risks scoring (1-10), the ship safety risks are summarised in Table 5-25, then the pairwise comparisons matrix Table 5-26 are obtained.

Table 5-25: Listed seven BWTS alternatives from BWTS1 to BWTS7, their disinfection method, their subjective assessment for their ship safety risks, risk sores (1-10) information from Table 5-21.

BWTS disinfection method	Denoted	Subjective ship safety risk	Ship safety risk score (1-10)
De-Oxygenation	BWTS1	Low	2
Ozone treatment	BWTS2	Medium	5
Chlorine dioxide treatment	BWTS3	Low	3
Chlorine treatment	BWTS4	Medium	5
Ultraviolet irradiation treatment (UV)	BWTS5	Low	2
Ultraviolet irradiation treatment (UV)	BWTS6	Low	2
Ultraviolet irradiation treatment (UV)	BWTS7	Low	2

Table 5-26: The AHP judgment matrix obtained of the maximum ship safety criterion for each of the given BWTS alternatives

Maximum ship safety	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	5.00	3.00	5.00	2.00	2.00	2.00
BWTS2	0.20	1.00	0.60	1.00	0.40	0.40	0.40
BWTS3	0.33	1.67	1.00	1.67	0.67	0.67	0.67
BWTS4	0.20	1.00	0.60	1.00	0.40	0.40	0.40
BWTS5	0.50	2.50	1.50	2.50	1.00	1.000	1.000
BWTS6	0.50	2.50	1.50	2.50	1.00	1.00	1.000
BWTS7	0.50	2.50	1.50	2.50	1.00	1.00	1.00

λ max = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is calculated as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-27.

Table 5-27: Listed priorities between the given BWTS alternatives for the maximum ship safety criterion

BWTS disinfection method	Denoted	Vector of priority for the Maximum ship safety
De-Oxygenation	BWTS1	0.309
Ozone treatment	BWTS2	0.062
Chlorine dioxide treatment	BWTS3	0.103
Chlorine treatment	BWTS4	0.062
Ultraviolet irradiation treatment (UV)	BWTS5	0.155
Ultraviolet irradiation treatment (UV)	BWTS6	0.155
Ultraviolet irradiation treatment (UV)	BWTS7	0.155

The result obtained from the pairwise comparisons, Table 5-27, the BWTS1 (0.309) is found as the most preferred alternative for satisfying *the maximum ship safety* amongst the given alternatives.

Due to the subjective/objective evaluation scoring risks (1-10) of each BWTS alternative according to the provided information from the literature review, the accuracy of the result may be influenced.

5.2.4.2.3 Maximum Crew Safety

Based on the subjective information and the objective risks scoring (1-10) of the ship safety risks are summarised in Table 5-28, then the pairwise comparisons matrix Table 5-29 are obtained.

Table 5-28: Listed seven BWTS alternatives from BWTS1 to BWTS7, their disinfection method, their subjective assessment for their crew safety risks, crew risk scores (1-10) obtain from Table 5-21

BWTS disinfection method	Denoted	Subjective crew safety risk	crew safety risk score (1-10)
De-Oxygenation	BWTS1	Low	2
Ozone treatment	BWTS2	Medium	5
Chlorine dioxide treatment	BWTS3	Low	3
Chlorine treatment	BWTS4	Medium	5
Ultraviolet irradiation treatment (UV)	BWTS5	Low	2
Ultraviolet irradiation treatment (UV)	BWTS6	Low	2
Ultraviolet irradiation treatment (UV)	BWTS7	Low	2

Table 5-29: The AHP judgment matrix obtained of the maximum crew safety criterion for each of the given BWTS alternatives

Maximum crew safety	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	2.50	2.50	1.50	1.00	1.00	1.00
BWTS2	0.40	1.00	1.00	0.60	0.40	0.40	0.40
BWTS3	0.40	1.00	1.00	0.60	0.40	0.40	0.40
BWTS4	0.67	1.67	1.67	1.00	0.67	0.67	0.67
BWTS5	1.00	2.50	2.50	1.50	1.00	1.000	1.000
BWTS6	1.00	2.50	2.50	1.50	1.00	1.00	1.000
BWTS7	1.00	2.50	2.50	1.50	1.00	1.00	1.00

λ max = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is calculated as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-30.

Table 5-30: Listed priorities between the given BWTS alternatives for the maximum crew safety criterion

BWTS disinfection method	Denoted	Vector of priority for the Maximum crew safety
De-Oxygenation	BWTS1	0.183
Ozone treatment	BWTS2	0.073
Chlorine dioxide treatment	BWTS3	0.073
Chlorine treatment	BWTS4	0.122
Ultraviolet irradiation treatment (UV)	BWTS5	0.183
Ultraviolet irradiation treatment (UV)	BWTS6	0.183
Ultraviolet irradiation treatment (UV)	BWTS7	0.183

The result obtained from the pairwise comparisons, Table 5-30, the BWTS2 (0.073) and BWTS3 (0.073) are shown as the least preferred alternatives for satisfying *the maximum crew safety* amongst the given alternatives.

Again it should be noted that due to the missing information, subjective assessment, result obtained may influence this result because it is based on subjective evaluation and scoring risks (1-10) of each BWTS alternative according to the provided information from the literature review.

5.2.4.3 Regulation

Meeting the regulation is tied with satisfying the bio-efficacy of a ballast water treatment, is a very important criterion which is associated with the ability of a BWTS to effectively reduce or/and eliminate harmful organisms from ballast water. However, studies found that bio-efficacy can be altered (or influenced) under the change of indicators (e.g. temperature, water chemistry, salinity, clarity). Therefore, in this study, the regulation for a BWTS for given ship in a certain geographic location and voyage is defined by the following indicators:

- Minimum influence on changes to seawater temperature
- Minimum influence on changes to seawater salinity
- Minimum influence on changes to seawater organic concentration

- Minimum influence on changes to seawater clarity

Since not all the required information about each BWTS alternative was provided by the vendors. These indicators were acquired from the subjective information found in the literature based on the disinfection method used by each BWTS alternative in Table 5-31.

In Table 5-31, subjective effects risks to bio-efficacy i.e. regulation aspects, were noted for each of the given disinfection method based on the information acquired from the relevant literature review. It is important to note, that after collecting the subjective information from the literature, a score from 1 to 10, where ‘high’ or 10 represents the worst score which is considered to have highest risk towards satisfying the criteria the *minimum influence to change of seawater temperature*, *salinity*, *organic concentration* and *clarity* were obtained for each of the given BWTS alternative, as shown in Table 5-31. On the other hand, lower scores are considered lower risks which are better scores to satisfy the regulation criterion by its sub-criteria.

Table 5-31: Subjective regulation assessment based on the influence of the temperature, salinity, seawater chemistry and clarity changes; a score from 1 to 10, where 10 represents the highest risk score to the criterion according to the literature review of the relevant studies.

BWTS	Regulation aspects	Subjective effects of temperature change (1-10)	Subjective effects of salinity (1-10)	Subjective effects of organic concentration (1-10)	Subjective effects of clarity (1-10)	References
Ozonation	• Residual oxidants more persistent in seawater than freshwater. • Influenced by material contained in water. • Sensitive to different waters chemical characteristics (e.g. pH, Salinity, nutrients such as phosphates, silicates, nitrates, nitrites, ammonia and total organic carbon (TOC)). • Different ports water will require different doses of ozone. • Decay of the total residual oxidant (TRO) was shown influenced by water salinity, organic matters, inorganic maters (iron), microorganisms, seasonal changes, temperature and light variation. • High dosage required.	• High (7)	• High (8)	• High (8)	• Low (2)	• (Gregg et al., 2009) • (Gottschalk et al., 2009) • (Sassi et al., 2005) • (Herwig et al., 2006) • (Von Gunten, 2003b) • (von Gunten, 2003a) • (Wright et al., 2010) • (Oemcke and van Leeuwen, 2005b) • (Oemcke and Van Leeuwen, 2005a) • (Jing et al., 2012)
Ultraviolet (UV) irradiation	• No by-products. • Effective bactericide and virucide • Not sensitive to temperature change. • Does differs to water qualities • Bio-fouling of lamps surfaces. • Sensitivity to water clarity	• Verylow (1)	• Very low (2)	• Very low (2)	• High (8)	• (Gregg et al., 2009) • (Severin et al., 1983) • (Jing et al., 2012) • (Sutherland et al., 2001) • (Xu et al., 2011) • (Sassi et al., 2005)
De-oxygenation	• Sensitive to water temperature.	• Low (2)	• Very low (1)	• Medium (5)	• Low (2)	• (Tamburri et al., 2002)

	• Sensitive to water chemistry (e.g. lowered pH) • Not influenced by water salinity. • Inversely related to temperature. • Can react with water chemistry such pH. 8-175 hrs or very long period of 10 days approximately.					• (McCollin et al., 2007a) • (Jing et al., 2012) • (de Lafontaine et al., 2013) • (de Lafontaine and Despatie, 2014)
Chlorination	• Sediments and organic material influence the treatment as well as Light/ darkness, season and location influence decay.	• High (7)	• High (8)	• Medium (5)	• Low (2)	• (Song et al., 2009) • (Carney, 2011) • (Gregg et al., 2009) • (Tsolaki et al., 2010) • (Matousek et al., 2006)
Chlorine Dioxide	• Degradation is influenced by temperature change (44hr) in warm water and longer in cold water (48hr). • Does concentration can change bio efficacy. • Degrade of 2 weeks. • Not influenced by organic material in water.	• Medium (6)	• Low (3)	• High (7)	• Low (2)	• (Gregg and Hallegraeff, 2007) • (Maranda et al., 2013) • (Gregg et al., 2009)

5.2.4.3.1 Minimum influence on changes to seawater temperature

The evaluations between two disinfection methods are obtained based on the subjective regulation aspects in Table 5-31. For example, when comparing the ozone with the UV treatments, it was noted from the literature that ozone treatment is more sensitive to water temperature, salinity, and organic concentrations, thus scoring high risks to change of temperature, salinity etc. On the other hand, the UV treatment was noted to be less sensitive to temperature change, salinity, organic concentration and therefore, scored lower than ozone on these aspects, but it was noted to be very sensitive to water clarity and purity, thus scoring higher than the ozone in this particular aspect. The same way of evaluation was carried out with the rest of the given BWTS alternatives.

Based on the subjective information and the objective scoring (1-10) of the risk to the influence of seawater temperature change, Table 5-31, on the bio-efficacy of the regulation evaluation of each BWTS are summarised in Table 5-32, then the pairwise comparisons matrix Table 5-33 are obtained.

Table 5-32: Listed seven BWTS alternatives from BWTS1 to BWTS7 by their disinfection method, their subjective assessment for their bio-efficacy risks to seawater temperature risks, and their risks scores (1-10) according to the information in Table 5-31.

BWTS disinfection method	Denoted	Subjective risks to change seawater temperature	Change of seawater temperature risk score (1-10)
De-Oxygenation	BWTS1	low	2
Ozone treatment	BWTS2	High	7
Chlorine dioxide treatment	BWTS3	Medium	6
Chlorine treatment	BWTS4	High	7
Ultraviolet irradiation treatment (UV)	BWTS5	Low	1
Ultraviolet irradiation treatment (UV)	BWTS6	Low	1
Ultraviolet irradiation treatment (UV)	BWTS7	Low	1

Table 5-33: The AHP judgment matrix obtained of the minimum effect to change of seawater temperature criterion for each of the given BWTS alternatives

Minimum effects to temp change	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	3.50	3.00	3.50	0.50	0.50	0.50
BWTS2	0.29	1.00	0.86	1.00	0.14	0.14	0.14
BWTS3	0.33	1.17	1.00	1.17	0.17	0.17	0.17
BWTS4	0.29	1.00	0.86	1.00	0.14	0.14	0.14
BWTS5	2.00	7.00	6.00	7.00	1.00	1.000	1.000
BWTS6	2.00	7.00	6.00	7.00	1.00	1.00	1.000
BWTS7	2.00	7.00	6.00	7.00	1.00	1.00	1.00

λ max = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is calculated as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-34.

Table 5-34: Listed priorities between the given BWTS alternatives for the minimum influence on changes to seawater temperature criterion

BWTS disinfection method	Denoted	Vector of priority for the minimum influence on changes to seawater temperature
De-Oxygenation	BWTS1	0.127
Ozone treatment	BWTS2	0.036
Chlorine dioxide treatment	BWTS3	0.042
Chlorine treatment	BWTS4	0.036
Ultraviolet irradiation treatment (UV)	BWTS5	0.253
Ultraviolet irradiation treatment (UV)	BWTS6	0.253
Ultraviolet irradiation treatment (UV)	BWTS7	0.253

The result obtained from the pairwise comparisons, Table 5-34, the BWTS2 and BWTS4 (0.036) equally are shown as the least preferred alternatives for satisfying *the minimum influence on changes to seawater temperature* criterion amongst the given alternatives.

Due to the subjective/ objective evaluations risks scores (1-10) of each BWTS alternative which is based on the aggregated information from the relevant literature review, the accuracy of obtained results may be influenced.

5.2.4.3.2 Minimum influence on changes to seawater salinity

Based on the subjective information and the objective scoring (1-10) the risks to *the influence of seawater salinity change*, Table 5-31, on the bio-efficacy of the BWTS are summarised in Table 5-35, then the pairwise comparisons matrix Table 5-36 are obtained.

Table 5-35: Listed seven BWTS alternatives from BWTS1 to BWTS7, by their disinfection method, their subjective assessment for their bio-efficacy risks upon the seawater salinity change risks, and their risks scores (1-10) according to the information in Table 5-31.

BWTS Disinfection method	Denoted	Subjective risks to change seawater salinity	Change of seawater salinity risk score (1-10)
De-Oxygenation	BWTS1	low	2
Ozone treatment	BWTS2	High	8
Chlorine dioxide treatment	BWTS3	Low	3
Chlorine treatment	BWTS4	High	8
Ultraviolet irradiation treatment (UV)	BWTS5	Low	2
Ultraviolet irradiation treatment (UV)	BWTS6	Low	2
Ultraviolet irradiation treatment (UV)	BWTS7	Low	2

Table 5-36: The AHP judgment matrix obtained of the minimum influence on changes to seawater salinity criterion for each of the given BWTS alternatives

Minimum effects to salinity change	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	4.00	1.50	4.00	1.00	1.00	1.00
BWTS2	0.25	1.00	0.38	1.00	0.25	0.25	0.25
BWTS3	0.67	2.67	1.00	2.67	0.67	0.67	0.67
BWTS4	0.25	1.00	0.38	1.00	0.25	0.25	0.25
BWTS5	1.00	4.00	1.50	4.00	1.00	1.000	1.000
BWTS6	1.00	4.00	1.50	4.00	1.00	1.00	1.000

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is calculated as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-37.

Table 5-37: Listed priorities between the given BWTS alternatives for the minimum influence on changes to seawater salinity

BWTS disinfection method	Denoted	Vector of priority for the influence on changes to seawater salinity
De-Oxygenation	BWTS1	0.194
Ozone treatment	BWTS2	0.048
Chlorine dioxide treatment	BWTS3	0.129
Chlorine treatment	BWTS4	0.048
Ultraviolet irradiation treatment (UV)	BWTS5	0.194
Ultraviolet irradiation treatment (UV)	BWTS6	0.194
Ultraviolet irradiation treatment (UV)	BWTS7	0.194

The result obtained from the pairwise comparisons, Table 5-37, the BWTS2 and BWTS4 equally (0.048) are shown as the least preferred alternatives for satisfying *the minimum influence on changes to seawater salinity* amongst the given alternatives. Due to the subjective/ objective evaluations risks scores (1-10) of each BWTS alternative which is based on the aggregated information from the relevant literature review, the accuracy of obtained results may be influenced.

5.2.4.3.3 Minimum influence on changes to seawater organic concentration

Based on the subjective information and the objective risks ranking (1-10) of the risk to the influence of seawater salinity change, Table5-31, on the bio-efficacy of the BWTS are summarised in Table 5-38, then the pairwise comparisons matrix Table 5-39 are obtained.

Table 5-38: Listed seven BWTS alternatives from BWTS1 to BWTS7 by their disinfection method, their subjective assessment for their regulation risks upon the seawater chemical property change risks, and their risks scores (1-10) according to the information in Table 5-31.

BWTS disinfection method	Denoted	Subjective risks to changes to seawater organic concentration	influence on changes to seawater organic concentration risk rank (1-10)
De-Oxygenation	BWTS1	medium	5
Ozone treatment	BWTS2	High	8
Chlorine dioxide treatment	BWTS3	High	7
Chlorine treatment	BWTS4	medium	5
Ultraviolet irradiation treatment (UV)	BWTS5	Low	2
Ultraviolet irradiation treatment (UV)	BWTS6	Low	2
Ultraviolet irradiation treatment (UV)	BWTS7	Low	2

Table 5-39: The AHP judgment matrix obtained of the minimum changes to seawater organic concentration criterion for each of the given BWTS alternatives

Minimum effects to chemical property change	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	1.60	1.40	1.00	0.40	0.40	0.40
BWTS2	0.63	1.00	0.88	0.63	0.25	0.25	0.25
BWTS3	0.71	1.14	1.00	0.71	0.29	0.29	0.29
BWTS4	1.00	1.60	1.40	1.00	0.40	0.40	0.40
BWTS5	2.50	4.00	3.50	2.50	1.00	1.000	1.000
BWTS6	2.50	4.00	3.50	2.50	1.00	1.00	1.000
BWTS7	2.50	4.00	3.50	2.50	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is calculated as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-40.

Table 5-40: Listed priorities between the given BWTS alternatives for the minimum influence changes to seawater organic concentration

BWTS disinfection method	Denoted	Vector of priority for the minimum influence changes to seawater organic concentration
De-Oxygenation	BWTS1	0.092
Ozone treatment	BWTS2	0.058
Chlorine dioxide treatment	BWTS3	0.066
Chlorine treatment	BWTS4	0.092
Ultraviolet irradiation treatment (UV)	BWTS5	0.231
Ultraviolet irradiation treatment (UV)	BWTS6	0.231
Ultraviolet irradiation treatment (UV)	BWTS7	0.231

The result obtained from the pairwise comparisons, Table 5-40, BWTS2 (0.058) and BWTS3 (0.066) treatments are shown as the least preferred alternatives for satisfying *minimum influence changes to seawater organic concentration* amongst the given alternatives. On the other hand all UV treatments have been equally selected as the preferred alternative amongst the given BWTS alternatives. Due to the subjective/objective evaluations risks scores (1-10) of each BWTS alternative which is based on the aggregated information from the relevant literature review, the accuracy of obtained results may be influenced.

5.2.4.3.4 Minimum influence changes to seawater clarity

Based on the subjective information and the objective scoring (1-10) the risks to the *influence of seawater salinity changes*, Table 5-31, on the regulation of each BWTS are summarised in Table 5-41, then the pairwise comparisons matrix Table 5-42 are obtained.

Table 5-41: Listed seven BWTS alternatives from BWTS1 to BWTS7 by their disinfection method, their subjective assessment for their bio-efficacy risks upon the seawater clarity change risks, and their risks scores (1-10) according to the information in Table 5-31.

BWTS disinfection method	Denoted	Subjective risks to change seawater clarity	Change of seawater clarity risk rank (1-10)
De-Oxygenation	BWTS1	low	2
Ozone treatment	BWTS2	low	2
Chlorine dioxide treatment	BWTS3	low	2
Chlorine treatment	BWTS4	low	2
Ultraviolet irradiation treatment (UV)	BWTS5	High	8
Ultraviolet irradiation treatment (UV)	BWTS6	High	8
Ultraviolet irradiation treatment (UV)	BWTS7	High	8

Table 5-42: The AHP judgment matrix obtained of the minimum influence changes to seawater clarity criterion for each of the given BWTS alternatives

Minimum effects to seawater clarity change	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	1.00	1.00	1.00	4.00	4.00	4.00
BWTS2	1.00	1.00	1.00	1.00	4.00	4.00	4.00
BWTS3	1.00	1.00	1.00	1.00	4.00	4.00	4.00
BWTS4	1.00	1.00	1.00	1.00	4.00	4.00	4.00
BWTS5	0.25	0.25	0.25	0.25	1.00	1.000	1.000
BWTS6	0.25	0.25	0.25	0.25	1.00	1.00	1.000
BWTS7	0.25	0.25	0.25	0.25	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij} = w_j/w_i$). The consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-43.

Table 5-43: Listed priorities between the given BWTS alternatives for the minimum influence changes to seawater clarity

BWTS disinfection method	Denoted	Vector of priority for the minimum influence changes to seawater clarity
De-Oxygenation	BWTS1	0.211
Ozone treatment	BWTS2	0.211
Chlorine dioxide treatment	BWTS3	0.211
Chlorine treatment	BWTS4	0.211
Ultraviolet irradiation treatment (UV)	BWTS5	0.053
Ultraviolet irradiation treatment (UV)	BWTS6	0.053
Ultraviolet irradiation treatment (UV)	BWTS7	0.053

The result obtained from the pairwise comparisons, Table 5-43, BWTS1-4 (0.211) are shown as the equally preferred alternatives for satisfying *the minimum influence changes to seawater clarity* alternatives. Due to the subjective/ objective evaluations risks scores (1-10) of each BWTS alternative which is based on the aggregated information from the relevant literature review, the accuracy of obtained results may be influenced.

5.2.4.4 Ship-compatibility

In this study, ship compatibility is considered as one of the most important aspects of the model which focuses on the physical applicability of using a ballast water treatment system (BWTS) on-board a given ship. Ship compatibility was evaluated by assessing the following important indicators as identified by the expert's interview chapter 4. The ship compatibility is evaluated according to the information of each identified criterion in the following sub-sections.

5.2.4.4.1 Satisfying limited space

In this study, satisfying the limited space focuses on the sizes between the given BWTS alternatives. This is because, in ships, normally the space can be one of the critical constraints that one ship may have. The information provided by each BWTS vendor is aggregated in Table 5-44. The information provided by each BWTS was subjectively evaluated against the identified criteria as shown in Table 5-44 for each BWTS alternative for the given VLCC.

In Table 5-44, the subjective evaluation for satisfying aspects to each criterion were noted for each of the given BWTS alternatives based on the information acquired from the BWTS vendor. After collecting the subjective information from the BWTS vendors, a score from 1 to 10 is given, where 10 represents the highest satisfying score, which is the highest satisfaction to the criterion to satisfy *the compact as one unit*, *can fit into hazardous place*, and *minimum number of equipment* as shown in Table 5-44. These information will be used in later sub sections accordingly.

Table 5-44: Aggregated information about each system foot print (m^2), subjective evaluation as compact as one unit possibility, can fit into hazardous place and the number of equipment's.

BWTS disinfection method	Denoted	Compact as one unit (1-10)	Can fit into a hazardous place (1-10)	Minimum number of equipment	Foot print (m^2)
De-Oxygenation	BWTS1	• High (7)	• High (8)	3	12.5
Ozone treatment	BWTS2	• low (2)	• Medium (5)	4	29.2
Chlorine dioxide treatment	BWTS3	• Low (2)	• Medium (5)	5	23.3
Chlorine treatment	BWTS4	• Low (2)	• High (8)	3	12.59
Ultraviolet irradiation treatment (UV)	BWTS5	• High (7)	• Medium (5)	3	14
Ultraviolet irradiation treatment (UV)	BWTS6	• High (7)	• Medium (5)	5	7.39
Ultraviolet irradiation treatment (UV)	BWTS7	• High (7)	• Medium (5)	4	9.83

5.2.4.4.1.1 Satisfying process time

Satisfying process time is defined by the following indicators:

- Satisfy ship operating mode;
- Satisfy ship voyage length of 14 days steam days;
- Satisfy ship voyage length of 24 days steam days.

In Table 5-45, subjective satisfying aspects to each criterion were noted for each of the given BWTS alternatives based on the information acquired from the BWTS vendor. After collecting the subjective information from the BWTS vendors, a score from 1 to 10 was given, where 10 represents the highest satisfying score, which is the highest satisfaction to the objective or criterion to *satisfy the ship operating mode and voyage length of 14 days steaming time*. The information will be used in later sub sections accordingly.

Table 5-45: listed disinfection methods, their process time aspects according to the literature review, and subjective satisfying ship operating mode, ship voyage length 14 days, ship voyage length 24 days.

BWTS	Process time	Satisfy ship operating mode (1-10)	Satisfy ship voyage length 14 days (1-10)	Satisfy ship voyage length 24 days (1-10)	References
Ozonation	• Suggested for long contact time from 6 hours to- one week's depending on the water quality, seawater temperature, salinity to obtain better disinfection results less environmental risks.	• low (2)	• Medium (6)	• High (8)	• (Gregg et al., 2009) • (Gottschalk et al., 2009) • (Sassi et al., 2005) • (Herwig et al., 2006) • (Von Gunten, 2003b) • (von Gunten, 2003a) • (Wright et al., 2010) • (Oemcke and van Leeuwen, 2005b) • (Oemcke and Van Leeuwen, 2005a) • (Jing et al., 2012)
Ultraviolet (UV) irradiation	• Short contact time • Re-treatment is recommended by BWTS vendors.	• High (7)	• High (8)	• High (8)	• (Gregg et al., 2009) • (Severin et al., 1983) • (Jing et al., 2012) • (Sutherland et al., 2001) • (Xu et al., 2011) • (Sassi et al., 2005)
De-oxygenation	• Long contact time from 2 weeks to obtain better disinfection results depending on the seawater temperature, pH.	• Low (2)	• Low (2)	• High (8)	• (Tamburri et al., 2002) • (McCollin et al., 2007a) • (Jing et al., 2012) • (de Lafontaine et al., 2013) • (de Lafontaine and Despatie, 2014)
Chlorination	• Suggested for long contact time from 6 hours to- one week's depending on the water quality, seawater temperature, salinity to obtain better disinfection results less environmental risks. • Sediments and organic material influence the treatment as well as	• low (2)	• Medium (6)	• High (8)	• (Song et al., 2009) • (Carney, 2011) • (Gregg et al., 2009) • (Tsolaki et al., 2010) • (Matousek et al., 2006)

	Light/ darkness, season and location influence decay. • Many by products and residual are similar compounds to ozonation.				
Chlorine Dioxide	• Degradation is influenced by seawater temperature change (44hr) in warm water and longer in cold water (48hr). • Does concentration can change bio efficacy. • Degrade of 2 weeks. • Not influenced by organic material in water.	• Low (2)	• Low (2)	• High (8)	• (Gregg and Hallegraeff, 2007) • (Maranda et al., 2013) • (Gregg et al., 2009)

5.2.4.4.2 Maximum ability to treat ship ballast water capacity

Satisfying the objective to maximum ability to treat ship ballast water capacity is collected from each BWTS vendor advertised ballast capacity. After that the capacities were evaluated against the requirement of 3000 m^3/hr pump capacity and a total of 6000 m^3/hr ballast water pump capacity for both pumps.

In Table 5-46, subjective information for satisfying the criterion to *maximum ability to treat ship ballast water capacity* was noted for each of the given BWTS alternatives based on the information acquired from the BWTS vendor. After collecting the subjective information from the BWTS vendors, a score from 1 to 10 is given, where 10 represents the highest satisfying score, which is the highest satisfaction to the criterion as shown in Table 5-46. Then the pairwise comparison matrix Table 5-47 is obtained.

Table 5-46: Aggregated information about each system ballast water capacity (m^3/h), subjective evaluations and objective evaluation (1-10) to satisfy ability to treat ship ballast water capacity.

BWTS disinfection method	Denoted	BWTS m^3/h Capacity	Satisfy ability to treat ship ballast water capacity (1-10)
De-Oxygenation	BWTS1	• **above 6000**	• **High (9)**
Ozone treatment	BWTS2	• **150 to 4000**	• **low (3)**
Chlorine dioxide treatment	BWTS3	• **Up to 9600**	• **High (9)**
Chlorine treatment	BWTS4	• **100 to 7000**	• **High (9)**
Ultraviolet irradiation treatment (UV)	BWTS5	• **20 Up to 3000**	• **High (9)**
Ultraviolet irradiation treatment (UV)	BWTS6	• **60 up to 6000**	• **High (7)**
Ultraviolet irradiation treatment (UV)	BWTS7	• **up to 3000**	• **Medium (5)**

Table 5-47: The AHP judgment matrix obtained of the maximum ability to treat ship ballast water capacity criterion for each of the given BWTS alternatives

Maximum ability to treat ship ballast water capacity	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS2	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS3	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS4	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS5	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS6	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS7	1.00	1.00	1.00	1.00	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-48.

Table 5-48: Listed priorities between the given BWTS alternatives for the maximum ability to treat ship ballast water capacity

BWTS disinfection method	Denoted	Vector of priority for the maximum ability to treat ship ballast water capacity
De-Oxygenation	BWTS1	0.160
Ozone treatment	BWTS2	0.060
Chlorine dioxide treatment	BWTS3	0.180
Chlorine treatment	BWTS4	0.180
Ultraviolet irradiation treatment (UV)	BWTS5	0.180
Ultraviolet irradiation treatment (UV)	BWTS6	0.140
Ultraviolet irradiation treatment (UV)	BWTS7	0.100

The result obtained from the pairwise comparisons, Table 5-48, BWTS2 (0.060) is shown as the least preferred alternative for satisfying *the maximum ability to treat ship ballast water capacity* criterion. On the other hand, BWTS3-5 (0.180) equally found as the most preferred alternatives amongst the given BWTS alternatives.

5.2.4.4.3 Minimum interruption at ship emergency

Minimum interruption to ship emergency system is defined as the ability of the ballast water treatment system not to interrupt the ship ballast system in the case of emergency. Generally, the IMO approval has considered that a BWTS does not interrupt ship ballast system in case of emergency. However, in this study, if the ship is using a specific system that depends on the degradation of the treatment inside the ballast water tanks then cautions of dumping big amount of chemicals into the environment may be considered as a limiting factor for using ship emergency.

According to the expert's interview (Chapter 4), this criterion was considered new and important when selecting a ballast treatment system. However, due to the lack of the information it is assumed that any BWTS that requires disinfection needs to be completed through the degradation of chemical and ballast water will have some interruption to ship ballast water emergency in Table 5-49. This can be arguably not true but it was chosen to be representing variations between the given BWTS. Then the pairwise comparisons matrix Table 5-50 are obtained.

Table 5-49: Aggregated information about each system ballast water method of disinfections and a subjective evaluations and objective evaluation (1-10) to minimum interruption to ship emergency system.

BWTS disinfection method	Denoted	Subjective minimum interruption to ship emergency system (1-10)
De-Oxygenation	BWTS1	High (7)
Ozone treatment	BWTS2	High (7)
Chlorine dioxide treatment	BWTS3	High (7)
Chlorine treatment	BWTS4	High (7)
Ultraviolet irradiation treatment (UV)	BWTS5	Low (2)
Ultraviolet irradiation treatment (UV)	BWTS6	Low (2)
Ultraviolet irradiation treatment (UV)	BWTS7	Low (2)

Table 5-50: The AHP judgment matrix obtained of minimum interruption to ship emergency system criterion for each of the given BWTS alternatives

minimum interruption to ship emergency system	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS2	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS3	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS4	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS5	3.50	3.50	3.50	3.50	1.00	1.000	1.000
BWTS6	3.50	3.50	3.50	3.50	1.00	1.00	1.000
BWTS7	3.50	3.50	3.50	3.50	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-51.

Table 5-51: Listed priorities between the given BWTS alternatives for the minimum interruption to ship emergency system

BWTS disinfection method	Denoted	Vector of priority for the minimum interruption to ship emergency system
De-Oxygenation	BWTS1	0.069
Ozone treatment	BWTS2	0.069
Chlorine dioxide treatment	BWTS3	0.069
Chlorine treatment	BWTS4	0.069
Ultraviolet irradiation treatment (UV)	BWTS5	0.241
Ultraviolet irradiation treatment (UV)	BWTS6	0.241
Ultraviolet irradiation treatment (UV)	BWTS7	0.241

The result obtained from the pairwise comparisons, Table 5-51, BWTS1-4 (0.069) are equally shown as the least preferred alternatives for satisfying *the minimum interruption at ship emergency* criterion. On the other hand BWTS5-7 have been equally found as the most preferred alternative amongst the given BWTS alternatives.

5.2.4.4.4 Maximum ease of operation

Maximum ease of operation about each BWTS alternative was provided by the vendors. The subjective ballast operation information used to evaluate the ease of operation of each BWTS Table 5-52.

In Table 5-52, the subjective maximum ease of operation aspects were noted for each of the given BWTS alternatives as acquired from the BWTS vendor. A score from 1 to 10, where 10 or ‘high’ represents the highest score, which is meant to highly satisfy the criterion *maximum ease of operation* for each of the given BWTS alternative, as shown in Table 5-52 and summarised in Table 5-53. Then the pairwise comparison matrix Table 5-54 is obtained.

Table 5-52: Aggregated ballast operations of each system ballast water capacity (m^3/h), subjective evaluations and objective evaluation score (1-10) to maximum ease of operation.

BWTS	BWTS disinfection method	Ballast operation	Subjective – maximum ease of operation (1-10)
1	De-Oxygenation	1- Ballasting: a. The SGG turns on and sends low-oxygen inert gas to Venturi Injectors. b. Ballast pumps then send ballast water through the Venturi Injectors. c. Cavitation with inert gas creates a micro fine bubble emulsion in water. d. Dissolved oxygen diffuses from the liquid phase into the gas phase bubbles 2- De-ballasting: • During de-ballasting, re-oxygenation upon release is rapid. Upon discharge below the water line, the ballast water once again passes through the Venturi Injectors, where air is re-introduced back into the water before release into the environment. • As water exits the ballast tanks, the tanks are filled with inert gas in order to maintain a low-oxygen condition, which has two key benefits: O When deoxygenated water is once again drawn into the ballast tanks, it will not re-oxygenate.	• Medium (5)
2	Ozone treatment	1- Ballasting: a. The Ozone generator which takes ambient air and strips away the nitrogen, concentrating the oxygen content. b. It passes the oxygen content through a high frequency electrical field to produce Ozone (O_3). c. The Ozone is then injected into the incoming ballast water to oxidize and neutralize entrained aquatic species 2- De-ballasting: • During de-ballasting chemicals that occur naturally in seawater, take place and TRO is checked before discharge.	• Medium (5)
3	Chlorine dioxide treatment	Ballasting: a. The Treatment System generates a dilute solution of chlorine dioxide as needed to treat incoming ballast water.	• High (8)

		b. A small amount of supply water is needed from the ship. The water can be seawater or fresh water and is only needed during ballasting. **c. A vacuum is created in the mixing chamber as the water passes through a specially designed venturi tube. Once this vacuum is established, the two precursor chemicals are introduced into the mixing chamber.** **d. The supply water then becomes a dilute solution of chlorine dioxide that is sent to the main ballast water line.** **2-** De-ballasting: • **proceeded as normal operation when the degradation took place inside ballast tanks.**	
4	Chlorine treatment	**1-** Ballasting: **a. The ballast water is filtrated by an automatic backwashing filter with 50µm screen to remove marine organisms larger than 50µm.** **b. Disinfection - A small side stream of the filtered ballast water is delivered to the electrolytic unit to generate the oxidants of high concentration (mainly sodium hypochlorite solution), then the oxidants are injected back into the main ballast stream to provide effective disinfection.** **c. Sodium hypochlorite solution as a very effective germicide can be kept in ballast water for a certain period to effectively kill the plankton, spores, larvae and pathogens contained in the ballast water to meet D-2 standard.** **2-** De-ballasting: • **During de-ballasting neutralization-the residual TRO level of the treated ballast water below 0.1ppm, then the treated ballast water can be directly discharged.**	• **High (8)**
5	Ultraviolet irradiation treatment (UV)	**1-** Ballasting: **a. The ballast water flows through 40 micron filter. The filter removes larger organisms and particles and back flushes them overboard at the ballasting location.** **b. After passing the filter, the ballast water continues through the UV chambers on its way to the ballast tanks. The UV light kills or inactivates organisms, viruses and bacteria in the ballast water.** **2-** De-ballasting:	• **High (8)**

		• The filter is automatically bypassed during de-ballasting, and the ballast water receives a second UV-treatment during discharge as a safeguard to ensure compliance.	
6	Ultraviolet irradiation treatment (UV)	Ballasting: a. The ballast water flows through 30-40 micron filter. The filter removes larger organisms and particles and back flushes them overboard at the ballasting location. b. After passing the filter, the ballast water continues through the UV chambers on its way to the ballast tanks. The UV light kills or inactivates organisms, viruses and bacteria in the ballast water. 2- De-ballasting: • The filter is automatically bypassed during de-ballasting, and the ballast water receives a second UV-treatment during discharge as a safeguard to ensure compliance.	• High (8)
7	Ultraviolet irradiation treatment (UV)	Ballasting: a. The Ballasting mode starts. In the mode, the ballast water from sea chest enters through the inlet pipe into the filter and flows through the cylindrical filter element from inside out. Organisms larger than 50㎛ are eliminated and those smaller than 50㎛ will pass into UV unit for disinfection. b. During filtration, sediments are accumulated on the surface of filter element and it is flushed out to overboard by the back flushing function without any disturbance on filter operation. 2- De-ballasting: 1. During de-ballasting mode, the ballast water from the ballast tanks passes through the UV unit to prevent reproduction of organisms and flows out to overboard. 2. During bypass mode, the ballast water skips filter and UV unit and simply flows out to overboard.	• High (8)

Table 5-53: Aggregated information about each system ballast water alternative, by their disinfection method, denoted from BWTS1 to BWTS7 and a subjective evaluations and objective evaluation scores (1-10) to maximum ease of operation from Table 5-52.

BWTS disinfection method	Denoted	Subjective maximum ease of operation (1-10)
De-Oxygenation	BWTS1	• Medium (5)
Ozone treatment	BWTS2	• Medium (5)
Chlorine dioxide treatment	BWTS3	• High (8)
Chlorine treatment	BWTS4	• High (8)
Ultraviolet irradiation treatment (UV)	BWTS5	• High (8)
Ultraviolet irradiation treatment (UV)	BWTS6	• High (8)
Ultraviolet irradiation treatment (UV)	BWTS7	• High (8)

Table 5-54: The AHP judgment matrix obtained of maximum ease of operation criterion for each of the given BWTS alternatives

Maximum ease of operation.	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	1.00	0.63	0.63	0.63	0.63	0.63
BWTS2	1.00	1.00	0.63	0.63	0.63	0.63	0.63
BWTS3	1.60	1.60	1.00	1.00	1.00	1.00	1.00
BWTS4	1.60	1.60	1.00	1.00	1.00	1.00	1.00
BWTS5	1.60	1.60	1.00	1.00	1.00	1.00	1.00
BWTS6	1.60	1.60	1.00	1.00	1.00	1.00	1.00
BWTS7	1.60	1.60	1.00	1.00	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the less ship risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-55.

Table 5-55: Listed priorities between the given BWTS alternatives for the maximum ease of operation

BWTS Disinfection method	Denoted	Vector of priority for the maximum ease of operation
De-Oxygenation	BWTS1	0.100
Ozone treatment	BWTS2	0.100
Chlorine dioxide treatment	BWTS3	0.160
Chlorine treatment	BWTS4	0.160
Ultraviolet irradiation treatment (UV)	BWTS5	0.160
Ultraviolet irradiation treatment (UV)	BWTS6	0.160
Ultraviolet irradiation treatment (UV)	BWTS7	0.160

The result obtained from the pairwise comparisons, Table 5-55, the BWTS1& 2 (0.100) equally were shown as the least preferred alternatives for *the maximum ease of operation*. On the other hand, the rest of the alternatives have been equally found as preferred alternative amongst the given BWTS alternatives.

5.2.4.4.5 Minimum ship operating cost

In this study, the minimum ship operating cost is defined according to the following indicators:

- Minimum requirement for extra expertise
- Minimum requirement for crew training
- Minimum fuel consumption
- Maximum ease for maintenance

The evaluation of the indicators above will determine the minimum ship operating cost. Evaluations of each indicator are discussed in details in the next sub section in this chapter.

5.2.4.4.6 Compact as one unit

Based on the information provided in Table 5- 44, which are summarised in Table 5-56. The pairwise comparisons matrix Table 5-57 are obtained.

Table 5-56: Listed information about each system ballast water alternative, disinfection method, denoted from BWTS1 to BWTS7 and a subjective evaluations and objective evaluation (1-10) to satisfy compact as one unit criterion.

BWTS disinfection method	Denoted	Compact as one unit (1-10)
De-Oxygenation	BWTS1	• High (7)
Ozone treatment	BWTS2	• Low (2)
Chlorine dioxide treatment	BWTS3	• Low (2)
Chlorine treatment	BWTS4	• Low (2)
Ultraviolet irradiation treatment (UV)	BWTS5	• High (7)
Ultraviolet irradiation treatment (UV)	BWTS6	• High (7)
Ultraviolet irradiation treatment (UV)	BWTS7	• High (7)

Table 5-57: The AHP judgment matrix obtained of satisfying compact as one unit criterion for each of the given BWTS alternatives

satisfying- compact as one unit	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	3.50	3.50	3.50	1.00	1.00	1.00
BWTS2	0.29	1.00	1.00	1.00	0.29	0.29	0.29
BWTS3	0.29	1.00	1.00	1.00	0.29	0.29	0.29
BWTS4	0.29	1.00	1.00	1.00	0.29	0.29	0.29
BWTS5	1.00	3.50	3.50	3.50	1.00	1.00	1.00
BWTS6	1.00	3.50	3.50	3.50	1.00	1.00	1.00
BWTS7	1.00	3.50	3.50	3.50	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the ship less risky alternative through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-58.

Table 5-58: Listed priorities between the given BWTS alternatives for the compact as one unit criterion

BWTS disinfection method	Denoted	Vector of priority for compact as one unit
De-Oxygenation	BWTS1	0.206
Ozone treatment	BWTS2	0.059
Chlorine dioxide treatment	BWTS3	0.059
Chlorine treatment	BWTS4	0.059
Ultraviolet irradiation treatment (UV)	BWTS5	0.206
Ultraviolet irradiation treatment (UV)	BWTS6	0.206
Ultraviolet irradiation treatment (UV)	BWTS7	0.206

The result obtained from the pairwise comparisons, Table 5-58, BWTS2-4 (0.059) equally shown as the least preferred alternatives for satisfying the compact as one unit criterion. On the other hand, the rest of the alternatives have been equally found as preferred alternative.

5.2.4.4.7 Can be installed in a hazardous place

Based on the information provided in Table 5-44, which is summarised in Table 5-59. The pairwise comparisons matrix Table 5-60 are obtained.

Table 5-59: Listed information about each system ballast water alternative, disinfection method, denoted from BWTS1 to BWTS7 and a subjective evaluations and objective evaluation (1-10) to satisfy can be installed in a hazardous place criterion.

BWTS disinfection method	Denoted	Can be installed in a hazardous place (1-10)
De-Oxygenation	BWTS1	• High (8)
Ozone treatment	BWTS2	• Medium (5)
Chlorine dioxide treatment	BWTS3	• Medium (5)
Chlorine treatment	BWTS4	• High (8)
Ultraviolet irradiation treatment (UV)	BWTS5	• Medium (5)
Ultraviolet irradiation treatment (UV)	BWTS6	• Medium (5)
Ultraviolet irradiation treatment (UV)	BWTS7	• Medium (5)

Table 5-60: The AHP judgment matrix obtained of satisfying can be installed in a hazardous place criterion for each of the given BWTS alternatives

satisfying- installed in a hazardous place	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	1.60	1.60	1.00	1.60	1.60	1.60
BWTS2	0.63	1.00	1.00	0.63	1.00	1.00	1.00
BWTS3	0.63	1.00	1.00	0.63	1.00	1.00	1.00
BWTS4	1.00	1.60	1.60	1.00	1.60	1.60	1.60
BWTS5	0.63	1.00	1.00	0.63	1.00	1.00	1.00
BWTS6	0.63	1.00	1.00	0.63	1.00	1.00	1.00
BWTS7	0.63	1.00	1.00	0.63	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 and considered consistent. The priority vector of the matrix obtained is shown in Table 5-61.

Table 5-61: Listed priorities between the given BWTS alternatives for the can be installed in a hazardous place criterion

BWTS Disinfection method	Denoted	Vector of priority for can be installed in a hazardous place
De-Oxygenation	BWTS1	0.195
Ozone treatment	BWTS2	0.122
Chlorine dioxide treatment	BWTS3	0.122
Chlorine treatment	BWTS4	0.195
Ultraviolet irradiation treatment (UV)	BWTS5	0.122
Ultraviolet irradiation treatment (UV)	BWTS6	0.122
Ultraviolet irradiation treatment (UV)	BWTS7	0.122

The result obtained from the pairwise comparisons, Table 5-61, BWTS1&4 (0.195) equally are shown as the most preferred alternative for satisfying system *can be installed in a hazardous place* criterion.

5.2.4.4.8 Minimum requirement to additional equipment

Based on the information provided in Table 5-44, which is summarised in Table 5-62. The pairwise comparisons matrix Table 5-63 are obtained.

Table 5-62: Listed information about each system ballast water alternative by their disinfection method, denoted from BWTS1 to BWTS7 and a subjective evaluations and objective evaluation (1-10) to satisfy can be installed in a hazardous place criterion.

Disinfection method	Denoted	Minimum number of equipment
De-Oxygenation	BWTS1	**3**
Ozone treatment	BWTS2	**4**
Chlorine dioxide treatment	BWTS3	**5**
Chlorine treatment	BWTS4	**3**
Ultraviolet irradiation treatment (UV)	BWTS5	**3**
Ultraviolet irradiation treatment (UV)	BWTS6	**5**
Ultraviolet irradiation treatment (UV)	BWTS7	**4**

Table 5-63: The AHP judgment matrix obtained of satisfying the minimum requirement to additional equipment criterion for each of the given BWTS alternatives

Minimum requirement to additional equipment	BWT S1	BWT S2	BWT S3	BWT S4	BWT S5	BWT S6	BWT S7
BWTS1	1.00	1.33	1.67	1.00	1.00	1.67	1.33
BWTS2	0.75	1.00	1.25	0.75	0.75	1.25	1.00
BWTS3	0.60	0.80	1.00	0.60	0.60	1.00	0.80
BWTS4	1.00	1.33	1.67	1.00	1.00	1.67	1.33
BWTS5	1.00	1.33	1.67	1.00	1.00	1.667	1.333
BWTS6	0.60	0.80	1.00	0.60	0.60	1.00	0.800
BWTS7	0.75	1.00	1.25	0.75	0.75	1.25	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-64.

Table 5-64: Listed priorities between the given BWTS alternatives for the minimum requirement to additional equipment criterion

BWTS Disinfection method	Denoted	Vector of priority for the minimum requirement to additional equipment
De-Oxygenation	BWTS1	0.175
Ozone treatment	BWTS2	0.132
Chlorine dioxide treatment	BWTS3	0.105
Chlorine treatment	BWTS4	0.175
Ultraviolet irradiation treatment (UV)	BWTS5	0.175
Ultraviolet irradiation treatment (UV)	BWTS6	0.105
Ultraviolet irradiation treatment (UV)	BWTS7	0.132

The result obtained from the pairwise comparisons, Table 5-64, BWTS6 and BWTS3 equally (0.105) are shown as the least preferred alternative for satisfying *the minimum requirement to additional equipment* criterion. On the other hand, BWTS1, 4 &5 equally (0.175) were found as the preferred alternative amongst other alternatives.

5.2.4.4.9 Satisfy ship operating mode

The operating mode of the given ship means the operating profile which confirms how the ship is normally operated according a scheduled operating or non-scheduled operating profile. The process time and length of operation of the BWTS alternatives were not provided by the vendor. Therefore, based evaluation of the disinfection method of each given BWTS alternative has been obtained as shown in Table 5-65. Then the pairwise comparisons matrix Table 5-66 were obtained.

Table 5-65: Listed information about each system ballast water alternative, disinfection method, denoted from BWTS1 to BWTS7 and a subjective evaluations and objective evaluation (1-10) to ship operating mode criterion.

BWTS disinfection method	Denoted	Satisfy ship operating mode (1-10)
De-oxygenation	BWTS1	• low (2)
Ozonation	BWTS2	• low (2)
Chlorine Dioxide	BWTS3	• Low (2)
Chlorination	BWTS4	• low (2)
Ultraviolet (UV) irradiation	BWTS5	• High (7)
Ultraviolet (UV) irradiation	BWTS6	• High (7)
Ultraviolet (UV) irradiation	BWTS7	• High (7)

Table 5-66: The AHP judgment matrix obtained of satisfying the minimum requirement to additional equipment criterion for each of the given BWTS alternatives

Satisfy ship operating mode	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS2	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS3	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS4	1.00	1.00	1.00	1.00	0.29	0.29	0.29
BWTS5	3.50	3.50	3.50	3.50	1.00	1.00	1.00
BWTS6	3.50	3.50	3.50	3.50	1.00	1.00	1.00
BWTS7	3.50	3.50	3.50	3.50	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-67.

Table 5-67: Listed priorities between the given BWTS alternatives for the minimum requirement to additional equipment criterion

BWTS disinfection method	Denoted	Vector of priority for the ship operating mode
De-Oxygenation	BWTS1	0.069
Ozone treatment	BWTS2	0.069
Chlorine dioxide treatment	BWTS3	0.069
Chlorine treatment	BWTS4	0.069
Ultraviolet irradiation treatment (UV)	BWTS5	0.241
Ultraviolet irradiation treatment (UV)	BWTS6	0.241
Ultraviolet irradiation treatment (UV)	BWTS7	0.241

The result obtained from the pairwise comparisons, Table 5-67, BWTS1-4 equally (0.069) are shown as the least preferred alternative for satisfying the *ship operating mode* criterion. On the other hand, BWTS5-7 equally (0.241) found as the preferred alternatives.

5.2.4.4.10 Satisfy ship voyage length

Satisfy ship voyage length for a given ship means that the process time of each BWTS alternatives should effectively be completed with the voyage length and before the VLCC reaches the port for loading cargo. However, the process time and length of operation of the BWTS alternatives were not provided by the vendor. Therefore, based evaluation of the disinfection method of each given BWTS alternative has been obtained as shown in Table 5-68. Here the process was subjectively evaluated against 14 days and 24 days. Then the pairwise comparisons matrix Table 5-69 and 5-70 was obtained.

Table 5-68: Listed information about each system ballast water alternative, disinfection method, denoted from BWTS1 to BWTS7 and a subjective evaluations and objective evaluation (1-10) to satisfy ship voyage length for 14 days voyage and 24 days voyage respectively.

BWTS disinfection method	Satisfy ship voyage length 14 days (1-10)	Satisfy ship voyage length 24 days (1-10)
De-oxygenation	• Low (2)	• High (8)
Ozonation	• Medium (6)	• High (8)
Chlorine Dioxide	• Low (2)	• High (8)
Chlorination	• Medium (6)	• High (8)
Ultraviolet (UV) irradiation	• High (8)	• High (8)
Ultraviolet (UV) irradiation	• High (8)	• High (8)
Ultraviolet (UV) irradiation	• High (8)	• High (8)

Table 5-69: The AHP judgment matrix obtained of satisfying ship voyage length 14 days criterion for each of the given BWTS alternatives

Satisfy ship voyage length 14 days	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	0.33	1.00	0.33	0.25	0.25	0.25
BWTS2	3.00	1.00	3.00	1.00	0.75	0.75	0.75
BWTS3	1.00	0.33	1.00	0.33	0.25	0.25	0.25
BWTS4	3.00	1.00	3.00	1.00	0.75	0.75	0.75
BWTS5	4.00	1.33	4.00	1.33	1.00	1.00	1.00
BWTS6	4.00	1.33	4.00	1.33	1.00	1.00	1.00
BWTS7	4.00	1.33	4.00	1.33	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 71.

Table 5-70: The AHP judgment matrix obtained of satisfying ship voyage length 24 days criterion for each of the given BWTS alternatives

Satisfy ship voyage length 24 days	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS2	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS3	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS4	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS5	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS6	1.00	1.00	1.00	1.00	1.00	1.00	1.00
BWTS7	1.00	1.00	1.00	1.00	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-72.

Table 5-71: Listed priorities between the given BWTS alternatives for ship voyage length 14 days criterion

BWTS disinfection method	Denoted	Vector of priority for the ship voyage length 14 days
De-Oxygenation	BWTS1	0.050
Ozone treatment	BWTS2	0.150
Chlorine dioxide treatment	BWTS3	0.050
Chlorine treatment	BWTS4	0.150
Ultraviolet irradiation treatment (UV)	BWTS5	0.200
Ultraviolet irradiation treatment (UV)	BWTS6	0.200
Ultraviolet irradiation treatment (UV)	BWTS7	0.200

Table 5-72: Listed priorities between the given BWTS alternatives for ship voyage length 24 days criterion

BWTS disinfection method	Denoted	Vector of priority for the ship voyage length 24 days
De-Oxygenation	BWTS1	0.143
Ozone treatment	BWTS2	0.143
Chlorine dioxide treatment	BWTS3	0.143
Chlorine treatment	BWTS4	0.143
Ultraviolet irradiation treatment (UV)	BWTS5	0.143
Ultraviolet irradiation treatment (UV)	BWTS6	0.143
Ultraviolet irradiation treatment (UV)	BWTS7	0.143

The result obtained from the pairwise comparisons for the BWTS alternatives against the two different voyages in length in Table 5-71 and Table 5-72, shows that during the 14 days voyage length is an important criterion when comparing between the alternatives for the given VLCC. For example, when the VLCC's voyage length is 14 days the BWTS1 (0.050) is shown as the least preferred alternative for satisfying the ship voyage length 14 days criterion. On the other hand, BWTS5-7 equally (0.200) found as the preferred alternatives as shown in Table 5-71.

However, when the VLCC's voyage length is 24 days, all the given BWTS are equally preferred for this voyage length as shown in Table 5-72.

5.2.4.4.11 Minimum requirement for extra expertise

The requirement for extra expertise depends on how sophisticated the ballast water system requires an engineer to be able to operate and maintain it during its life. Due to the lack of information, subjective aspects about each BWTS have been noted and then a subjective evaluation and objective score (1-10) of each ballast water system was given. A score from 1 to 10, where 10 represents the highest score, which is meant to highly satisfy the objective or criteria *minimum requirement for extra expertise and minimum requirement for crew training* were obtained for each of the given BWTS alternatives, as shown in Table 5-73. On the other hand, if a low score is given, it means that it is the worst score to satisfy the criterion. The pairwise comparison matrix Table 5-74 is obtained.

Table 5-73: listed operation aspects of each ballast water alternative, subjective evaluation for minimum requirement for extra expertise, requirement for crew training, and their rank (1-10) for each ballast water alternative.

BWTS	Denoted	Operation aspects	Minimum requirement for extra expertise (1-10)	Minimum requirement for crew training (1-10)
De-Oxygenation	BWTS1	• Stripping Gas Generator (SGG) can be used as similar way as the Topping Generator for Crude Oil Tankers. • The system is not using a new equipment to treat ballast water. • No storage is required. • No training is needed for operating the system.	• High (8)	• High (8)
Ozone treatment	BWTS2	• The system uses Ozone generator takes ambient air and strips away the nitrogen, concentrating the oxygen content – which is then passed through a high voltage or high frequency electrical field to produce ozone. • Good understanding is required for how the O_3 is produced. • How the Ozone reacts with other chemicals in seawater to produce the by-products requires good understanding. • Understanding how to measure the degradation of the by-products is essential.	• Low (2)	• Low (2)
Chlorine dioxide treatment	BWTS3	• The system consist of Chlorine Dioxide Generator(self-contained chemical storage tanks) associated piping, valves which requires good understanding of how the chemicals are blended to produce Clo_2. • The required dose and how to assess the optimum dose requires more understanding.	• Low (2)	• Low (2)
Chlorine treatment	BWTS4	• The system uses the Electrolysis Unit as a way for treating ballast water. • Understanding how the sodium hypochlorite is produced through the direct current passage between the anode (positive pole) and cathode (negative pole) to separate salt and water into basic elements. • How the chemical reaction to form sodium hypochlorite and hypochlorous acid required good understanding. • The other matter of this system is the understanding of the neutralization of free halogen (hypochlorite and hypobromite), in this system sodium thiosulfate at 1ppm before discharging ballast water. • Operating this system is not complicated.	• Low (2)	• High (7)
Ultraviolet irradiation treatment (UV)	BWTS5	• The system is based on the use of filtration and UV light for treating ballast water.	• High (8)	• High (8)

		• does not use or generate chemicals or biocides in its treatment or cleaning processes • The system does not use or generate chemicals or biocides in its treatment or cleaning processes. • No training is needed for operating the system. • Dose optimisation is required for better disinfection. • The self-Cleaning requires some understanding.		
Ultraviolet irradiation treatment (UV)	BWTS6	• The system uses high intensity ultraviolet (UV) treatment for the ballast water. • does not use or generate chemicals or biocides in its treatment or cleaning processes • No training is needed for operating the system • Dose optimisation is required for better disinfection. • The self-Cleaning requires some understanding.	• High (8)	• High (8)
Ultraviolet irradiation treatment (UV)	BWTS7	• The system uses a medium-pressure ultra violet (MPUV) lamps and filtration for treating the ballast water. • does not use or generate chemicals or biocides in its treatment or cleaning processes • No training is needed for operating the system • Dose optimisation is required for better disinfection.	• High (8)	• High (8)

Table 5-74: The AHP judgment matrix obtained of satisfying the minimum requirement for extra expertise criterion for each of the given BWTS alternatives

Satisfy Minimum requirement for extra expertise	BWT S1	BWT S2	BWT S3	BWT S4	BWT S5	BWT S6	BWT S7
BWTS1	1.00	4.00	4.00	4.00	1.00	1.00	1.00
BWTS2	0.25	1.00	1.00	1.00	0.25	0.25	0.25
BWTS3	0.25	1.00	1.00	1.00	0.25	0.25	0.25
BWTS4	0.25	1.00	1.00	1.00	0.25	0.25	0.25
BWTS5	1.00	4.00	4.00	4.00	1.00	1.00	1.00
BWTS6	1.00	4.00	4.00	4.00	1.00	1.00	1.00
BWTS7	1.00	4.00	4.00	4.00	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5- 75.

Table 5-75: Listed priorities between the given BWTS alternatives for minimum requirement for extra expertise criterion

BWTS disinfection method	Denoted	Vector of priority for minimum requirement for extra expertise
De-Oxygenation	BWTS1	0.211
Ozone treatment	BWTS2	0.053
Chlorine dioxide treatment	BWTS3	0.053
Chlorine treatment	BWTS4	0.053
Ultraviolet irradiation treatment (UV)	BWTS5	0.211
Ultraviolet irradiation treatment (UV)	BWTS6	0.211
Ultraviolet irradiation treatment (UV)	BWTS7	0.211

The result obtained from the pairwise comparisons, Table 5-75, BWTS2-4 equally (0.053) were found as the least preferred alternative for satisfying *the minimum requirement for extra expertise* criterion.

5.2.4.4.12 Minimum requirement for crew training

Based on the information provided in Table 5-73, the pairwise comparisons matrix Table 5-76 are obtained.

Table 5-76: The AHP judgment matrix obtained of satisfying the minimum requirement for crew training criterion for each of the given BWTS alternatives

Satisfy Minimum requirement for crew training	BWT S1	BWT S2	BWT S3	BWT S4	BWT S5	BWT S6	BWT S7
BWTS1	1.00	4.00	4.00	1.14	1.00	1.00	1.00
BWTS2	0.25	1.00	1.00	0.29	0.25	0.25	0.25
BWTS3	0.25	1.00	1.00	0.29	0.25	0.25	0.25
BWTS4	0.88	3.50	3.50	1.00	0.88	0.88	0.88
BWTS5	1.00	4.00	4.00	1.14	1.00	1.00	1.00
BWTS6	1.00	4.00	4.00	1.14	1.00	1.00	1.00
BWTS7	1.00	4.00	4.00	1.14	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-77.

Table 5-77: Listed priorities between the given BWTS alternatives for minimum requirement t for crew training criterion

BWTS disinfection method	Denoted	Vector of priority for minimum requirement for crew training
De-Oxygenation	BWTS1	0.186
Ozone treatment	BWTS2	0.047
Chlorine dioxide treatment	BWTS3	0.047
Chlorine treatment	BWTS4	0.163
Ultraviolet irradiation treatment (UV)	BWTS5	0.186
Ultraviolet irradiation treatment (UV)	BWTS6	0.186
Ultraviolet irradiation treatment (UV)	BWTS7	0.186

The result obtained from the pairwise comparisons, Table 5-77, BWTS2 and BWTS3 are equally (0.047) found as the least preferred alternative for satisfying *minimum requirement for crew training* criterion.

5.2.4.4.13 Minimum fuel consumption

Fuel consumption means the amount in litres or kilograms of fuel consumed by the given BWTS alternatives for any given time. In order to be able to calculate the fuel consumption of ballast water treatment, the lower calorific value (LCV) of a typical marine heavy fuel diesel is 41,000.00 KJ/Kg (Entec, 2002). The fuel consumption for each of the BWTS alternatives for the given VLCC can be found by equation (5-2) (Woodyard, 2004):

$$M = \frac{P_{kw} * t_s}{\eta_G * LCV} \qquad (5\text{-}2)$$

"M" is the fuel mass consumption (kg); "P_{kw}" is the power consumption (kW); "η_G" is the generator thermal efficiency i.e. assumed to be (42%) for a typical VLCC; "LCV" is the lower calorific value (LCV).

Conversion of the BWTS alternatives power consumption into fuel consumption for each of the BWTS alternatives is given in Table 5-78. Based on the information in Table 5-78, the pairwise comparisons matrix are obtained in Table 5-79.

Table 5-78: listed estimation of fuel consumption conversion for each BWTS alternatives

BWTS disinfection method	Denoted	Power consumption for BW capacity of 3000 m^3/h (kW)	Fuel consumption (kg)
De-Oxygenation	BWTS1	**129**	9100.00
Ozone treatment	BWTS2	**211**	14884.00
Chlorine dioxide treatment	BWTS3	**21**	1481.00
Chlorine treatment	BWTS4	**100**	7054.00
Ultraviolet irradiation treatment (UV)	BWTS5	**360**	25395.00
Ultraviolet irradiation treatment (UV)	BWTS6	**228**	16084.00
Ultraviolet irradiation treatment (UV)	BWTS7	**210**	14814.00

Table 5-79: The AHP judgment matrix obtained of satisfying the minimum fuel consumption criterion for each of the given BWTS alternatives

Minimum fuel consumption	BWTS1	BWTS2	BWTS3	BWTS4	BWTS5	BWTS6	BWTS7
BWTS1	1.00	1.64	0.16	0.78	2.79	1.77	1.63
BWTS2	0.61	1.00	0.10	0.47	1.71	1.08	1.00
BWTS3	6.14	10.05	1.00	4.76	17.14	10.86	10.00
BWTS4	1.29	2.11	0.21	1.00	3.60	2.28	2.10
BWTS5	0.36	0.59	0.06	0.28	1.00	0.633	0.583
BWTS6	0.57	0.93	0.09	0.44	1.58	1.00	0.921
BWTS7	0.61	1.00	0.10	0.48	1.71	1.09	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-80.

Table 5-80: Listed priorities between the given BWTS alternatives for minimum fuel consumption criterion

BWTS disinfection method	Denoted	Vector of priority for minimum fuel consumption
De-Oxygenation	BWTS1	0.094
Ozone treatment	BWTS2	0.058
Chlorine dioxide treatment	BWTS3	0.580
Chlorine treatment	BWTS4	0.122
Ultraviolet irradiation treatment (UV)	BWTS5	0.034
Ultraviolet irradiation treatment (UV)	BWTS6	0.053
Ultraviolet irradiation treatment (UV)	BWTS7	0.058

The result obtained from the pairwise comparisons, Table 5-80, BWTS5 (0.033) is shown as the least preferred alternative for satisfying *the minimum fuel consumption* criterion. On the other hand, BWTS3 (0.580) has been found as the most preferred alternative.

5.2.4.4.14 Maximum ease for maintenance

Table 5-81 shows the subjective ease of maintenance aspects which were noted for each of the given BWTS alternates, were based on the information provided for each BWTS vendor. In is important to note, that the subjective information provided a score from 1 to 10, where 10 represents the highest score which satisfy the criterion *maximum ease of maintenance* for each of the given BWTS alternative, as shown in Table 5-81. The lower the score, the less likely to satisfy the criterion. For example, when comparing between two disinfection treatments such as ozone and UV, the ozone was noted to have generators and pumps that requires specific maintenance procedures, therefore scored lower than UV treatment. On the other hand, the UV was noted with minor maintenance aspects such as cleaning filters or replacing UV lamps, thus scoring higher than ozone treatment. The de-oxygenation had many potentials as a BWTS alternative, but it was noted with SGG and other system components which were evaluated to require particular maintenance, thus scoring lower than UV treatment. The same evaluation method is done with the rest of the BWTS alternatives.

Then the pairwise comparisons matrix are obtained in Table 5-82.

Table 5-81: listed ballast water alternatives denoted from BWTS1 to BWTS7, subjective aspects about the ease of maintenance comparison between the given BWTS, and score (1-10) for each BWTS alternative.

BWTS disinfection method	Denoted	Maintenance aspects	Subjective - maximum ease for maintenance (1-10)
De-Oxygenation	BWTS1	• Protects ballast water tank coatings, sacrificial anodes and steel structure against the effect of corrosion. • Reduces the cost of coating maintenance. • Reduces corrosion up to 84% lower corrosion. • No filters, so no replacement or cleaning needed. • Venture injectors, does not have moving part and thus maintenance is low. • SGG may require maintenance but not much information is available. • No storage is required or topping up for the system. • Crew training is required to carry out maintenance on the SGG and system in case of fault.	• Low (2)
Ozone treatment	BWTS2	• System consists of two generators i.e. ozone and oxygen, but no information of maintenance provided. • Pumps in the system may require maintenance at a certain intervals. • No storage is required or topping up for the system. • Crew training is required to carry out maintenance on the generators and system in case of fault.	• Low (2)
Chlorine dioxide treatment	BWTS3	• System requires generating dilute solution of CLO_2 and supplying water which requires crew training to keep system maintained in case of fault. • Venture tube does not require maintenance. • Filter will require cleaning and/or replacement at certain intervals. • Storage is required topping up for the dilution system. • Pumps in the system may require maintenance at a certain intervals • Crew training & expertise of how the system works is required to carry out maintenance correctly and effectively in case of fault	• Low (2)
Chlorine treatment	BWTS4	• Filter will require cleaning and/or replacement at certain intervals. • Scarce information on maintenance for the electrolysis units. • Crew training & expertise of how the system works is required to carry out maintenance correctly and effectively in case of fault. • No storage is required or topping up for the system. • Checking TRO and neutralizer solution requires more training for crew.	• High (8)

Ultraviolet irradiation treatment (UV)	BWTS5	• **Filter will require cleaning and/or replacement at certain intervals.** • **UV Lamp replacement after 3000 hours of operations or breakage** • **Adjustment to the UV transmittance and sensors check.** • **Self-cleaning mechanism increase the low maintenance requirement.** • **No storage is required or topping up for the system.**	• **High (8)**
Ultraviolet irradiation treatment (UV)	BWTS6	• **Filter will require cleaning and/or replacement at certain intervals.** • **UV Lamp replacement after 5000 hours of operations or breakage** • **An automatic wiping mechanism increases the low maintenance requirement.** • **No storage is required or topping up for the system.**	• **High (8)**
Ultraviolet irradiation treatment (UV)	BWTS7	• **Filter will require cleaning and/or replacement at certain intervals.** • **UV Lamp (medium pressure) replacement after hours of operations or breakage** • **An automatic wiping mechanism increases the low maintenance requirement.** • **No storage is required or topping up for the system.**	• **High (8)**

Table 5-82: The AHP judgment matrix obtained of satisfying the maximum ease for maintenance criterion for each of the given BWTS alternatives

Maximum ease of maintenance	BWTS 1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7
BWTS1	1.00	1.00	1.00	0.25	0.25	0.25	0.25
BWTS2	1.00	1.00	1.00	0.25	0.25	0.25	0.25
BWTS3	1.00	1.00	1.00	0.25	0.25	0.25	0.25
BWTS4	4.00	4.00	4.00	1.00	1.00	1.00	1.00
BWTS5	4.00	4.00	4.00	1.00	1.00	1.00	1.00
BWTS6	4.00	4.00	4.00	1.00	1.00	1.00	1.00
BWTS7	4.00	4.00	4.00	1.00	1.00	1.00	1.00

λ_{max} = 7.00, Consistency Index C.I. = 0.00, Consistency Ratio C.R. = 0.00

The priority vector of the alternatives through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). The calculated consistency ratio (CR) is obtained as 0.00 which is consistent. The priority vector of the matrix obtained is shown in Table 5-83.

Table 5-83: Listed priorities between the given BWTS alternatives for the maximum ease of maintenance criterion

BWTS disinfection method	Denoted	Vector of priority for maximum ease for maintenance
De-Oxygenation	BWTS1	0.053
Ozone treatment	BWTS2	0.053
Chlorine dioxide treatment	BWTS3	0.053
Chlorine treatment	BWTS4	0.211
Ultraviolet irradiation treatment (UV)	BWTS5	0.211
Ultraviolet irradiation treatment (UV)	BWTS6	0.211
Ultraviolet irradiation treatment (UV)	BWTS7	0.211

The result obtained from the pairwise comparisons, Table 5-83, BWTS 1-3 are equally (0.053) shown as the least preferred alternative for satisfying *maximum ease for maintenance* criterion among the rest of the other alternatives.

5.3 Expert evaluations

The evaluations or judgments of the criteria used by the developed decision support model, that is by comparing between two criteria under a common parent has been done though developed web-based questionnaire. The expert is the head of the technical department in a well-known oil shipping company. The questionnaire has used the 1-9 scale of absolute numbers to assign numerical values of judgments or preferences made by comparing two criteria. The obtained judgments are collected from the questionnaire and calculated the priority vectors of the matrix as shown in Table 5-84 and Table 5-85.

Table 5-84: Calculated priority vectors of the identified global criteria based on the obtained preferences from the questionnaire (2nd level of AHP hierarchy structure)

Preferences on global criteria (2nd level)	**Combined priority vector**
Cost	0.042
Safety	0.286
Regulation	0.515
Ship Compatibility	0.157
	$\sum$ =1.00

λ_{max} = 4.17, Consistency Index C.I. = 0.05, Consistency Ratio C.R. = 0.06

The priority vector of the given criteria through the pairwise comparisons was performed in the form of ($a_{ij}= w_j/w_i$). According to the priority vector, Table 5-84, which the decision maker valued regulation as the most important criteria, followed by the safety criterion and then the ship compatibility and the least important criteria is the cost.

The priority vector, Table 5-85, shows that the decision maker valued all the cost, the safety and the regulation indicators as equally important each under its own parent node. On the other hand, minimising ship operating cost is shown as the important criterion followed by both maximising ability of the BWTS to treat ship ballast water capacity and minimising the interruption at ship emergency. Thereafter, the maximum ease of operation criterion becomes important, and the least important aspect is satisfying limited space criterion.

It is worth noting that, the calculated consistency ratio (CR) was obtained equal to 0.06, as shown in Table 5-85. This is because the decision maker was very reluctant to retake the questionnaire to satisfy 10 percent cut-off suggested by (Saaty, 1980). This is not a major problem; however, the sensitivity analysis will indicate whether such a variation is a problem or not as will be discussed in chapter 7.

Table 5-85: Calculated priority vectors of identified sub criteria based on the assumed experts judgments (3rd level of the AHP hierarchy structure)

Preferences on sub criteria (3rd level)	Combined priority Vector
Minimum capital cost (C1)	0.33
Minimum operating cost (C2)	0.33
Minimum maintenance cost (C3)	0.33
	∑ =1.00
Maximum environmental safety (S1)	0.33
Maximum ship safety (S2)	0.33
Maximum crew safety (S3)	0.33
	∑ =1.00
Minimum influence on changes to seawater temperature (B1)	0.250
Minimum influence on changes to seawater salinity (B2)	0.250
Minimum influence on changes to seawater organic concentration (B3)	0.250
Minimum influence on changes to seawater clarity (B4)	0.250
	∑ =1.00
Satisfying limited space (SH1)	0.124
Satisfying process time (SH2)	0.157
Maximum ability to treat ship ballast water capacity (SH3)	0.187
Minimum interruption to ship emergency system (SH4)	0.187
Maximum ease of operation (SH5)	0.125
Minimum ship operating cost (SH6)	0.220
	∑ =1.00

The obtained priority vector, Table 5-86, shows that the decision maker valued both the compact as one unit and the can be installed in a hazardous place criterion as more important than the minimising requirement to additional equipment for the given BWTS. The obtained priority vector, Table 5-86, also show the decision maker valued the criterion of satisfying ship operating mode more than satisfy ship voyage length.

Finally the priority vector, Table 5-86, also showed that the decision maker valued the criterion of minimising the fuel consumption as the most important criterion, followed by maximising the ease for maintenance. After that the minimum requirement for crew training criterion become important and the least important criteria is the minimum requirement for extra expertise.

Again the calculated consistency ratio (CR) was obtained less or equal to 0.01, and considered consistent as shown in Table 5-86.

Table 5-86: Calculated priority vectors of identified criteria based on the decision maker judgments (4th level of the AHP hierarchy structure)

Preferences on sub-sub criteria (4nd level)	**Combined priority Vector**
Compact as one unit (SH1-A)	0.40
Can be installed in a hazardous place (SH1-B)	0.40
Minimum requirement to additional equipment (SH1-C)	0.20
	∑ =1.00
Satisfy ship operating mode (SH2-A)	0.80
Satisfy ship voyage length (SH2-B)	0.20
	∑ =1.00
Minimum requirement for extra expertise (SH6-A)	0.125
Minimum requirement for crew training (SH6-B)	0.208
Minimum fuel consumption (SH6-C)	0.375
Maximum ease for maintenance (SH6-D)	0.292
	∑ =1.00

5.4 Table of all the aggregated and evaluated information

The aggregated evaluations based on all the information discussed in this chapter which were both important and required by the decision support model are shown in Table 5-87.

Table 5-87: The aggregated vectors of priorities based on the aggregated information from the BWTS alternatives, the VLCC and voyage information, and the decision maker of the shipping company.

Criteria required by AHP Model	Denote	Indicators meaning	Tangible?	Ballast water alternatives (input)							Decision maker priorities (input)	
				BWTS1	BWTS 2	BWTS 3	BWTS 4	BWTS 5	BWTS 6	BWTS 7		
Cost	**C1**	Minimum capital cost	yes	0.094	0.074	0.342	0.087	0.134	0.134	0.134	**0.33**	**0.042**
	C2	Minimum operating cost	yes	0.068	0.062	0.308	0.058	0.168	0.168	0.168	**0.33**	
	C3	Minimum maintenance cost	No	0.177	0.071	0.044	0.177	0.177	0.177	0.177	**0.33**	
Safety	**S1**	Maximum environmental safety	No	0.183	0.073	0.122	0.073	0.183	0.183	0.183	**0.33**	**0.286**
	S2	Maximum ship safety	No	0.309	0.062	0.103	0.062	0.155	0.155	0.155	**0.33**	
	S3	Maximum crew safety	No	0.183	0.073	0.073	0.122	0.183	0.183	0.183	**0.33**	
Regulation	**B1**	Minimum influence on changes to seawater temperature	No	0.127	0.036	0.042	0.036	0.253	0.253	0.253	**0.250**	**0.515**
	B2	Minimum influence on changes to seawater salinity	No	0.324	0.041	0.108	0.041	0.162	0.162	0.162	**0.250**	
	B3	Minimum influence on changes to seawater organic concentration	No	0.092	0.058	0.066	0.092	0.231	0.231	0.231	**0.250**	
	B4	Minimum influence on changes to seawater clarity	No	0.211	0.211	0.211	0.211	0.053	0.053	0.053	**0.250**	
Ship-Compatibility (VLCC)	**SH1**	Satisfying limited space	No								**0.124**	**0.157**
	SH2	Satisfying process time	No								**0.157**	
	SH3	Maximum ability to treat ship ballast water capacity	No	0.143	0.143	0.143	0.143	0.143	0.143	0.143	**0.187**	
	SH4	Minimum interruption to ship emergency system	No	0.069	0.069	0.069	0.069	0.241	0.241	0.241	**0.187**	
	SH5	Maximum ease of operation	No	0.1	0.1	0.16	0.16	0.16	0.16	0.16	**0.125**	
	SH6	Minimum Ship operating cost	No								**0.220**	
SH1	**SH1-A**	Compact as one unit	No	0.206	0.059	0.059	0.059	0.206	0.206	0.206	**0.40**	
	SH1-B	Can be installed in a hazardous place	No	0.211	0.053	0.132	0.211	0.132	0.132	0.132	**0.40**	
	SH1-C	Minimum requirement to additional equipment	Yes	0.175	0.132	0.105	0.175	0.175	0.105	0.132	**0.20**	
SH2	**SH2-A**	Satisfy ship operating mode	No	0.069	0.069	0.069	0.069	0.241	0.241	0.241	**0.80**	
	SH2-B	Satisfy ship voyage length	No	0.05	0.15	0.05	0.15	0.2	0.2	0.2	**0.20**	
SH6	**SH6-A**	Minimum requirement for extra expertise	No	0.211	0.053	0.053	0.053	0.211	0.211	0.211	**0.125**	

	SH6-B	Minimum requirement for crew training	No	0.186	0.047	0.047	0.163	0.186	0.186	0.186	**0.208**	
	SH6-C	Minimum fuel consumption	Yes	0.094	0.058	0.580	0.122	0.034	0.053	0.058	**0.375**	
	SH6-D	Maximum ease for maintenance	No	0.053	0.053	0.053	0.211	0.211	0.211	0.211	**0.292**	

5.5 Summary

In this chapter the collection of the necessary data and aggregation of the required information were discussed in details. The chapter have also discussed the steps and the types of data used as inputs to the developed model from an actual case-study. The decision support model required three important inputs of different types of data:

- Decision maker evaluations to each identified criterion in the model;
- VLCC particulars and voyage data;
- Finally, data about each ballast water treatment system (BWTS).

It is important to appreciate that it was not possible to acquire data from BWTS vendors for confidentiality reasons. This was a major shift in our study and thus acquiring missing data from relevant literature review and BWTS vendor websites and/or catalogues were necessary to complete the study. Seven typical BWTS were randomly selected and analysed as alternatives for the given VLCC.

It is worth noting that, the availability of the required data and the aggregation of the necessary information and approximations would influence the output of the model. This is because of the lack of necessary data which were aggregated from second hand sources and approximated as inputs to the model in this study. In addition, time constraint of the research and the limited budgets were also key limiting factors for the number of the selected BWTS alternatives and on how the study was chosen to be completed. The inconsistencies of all the evaluations for each matrix table have been checked to be less or 10 percent limited as suggested by (Saaty, 1980). However, decision maker evaluations had shown to be slightly more the 10 percent and this required the decision maker to revise his judgments. This process was found to be a difficult process, thus the decision maker was reluctant to proceed. Therefore, an evaluation by the decision maker will be completed in this study by the sensitivity analysis which will allow more investigation of this issue in chapter 7. Table 5-87 shows that the data inputs to decision support model which have considered both subjective (and intangible) data and tangible (or objective) data in order to compare between the seven BWTS alternatives for the VLCC under its specific voyage.

In chapter 6, the obtained results of the aggregated information and evaluation will be presented using the decision support model and analysis will be discussed in more details.

Chapter 6: Results and Discussion

6.0 Introduction

In this chapter, the derived results or the outcome of the decision support tool are discussed in detail. These results are based on the collected and aggregated data of the three inputs to the model as presented and discussed in chapter 5.

The outcome of the developed model is based on actual data of the case study presented and discussed before more analysis to validate the outcome in chapter 7. In the case study**,** the decision maker is faced with a difficult decision to select one out of seven BWTS alternatives for his VLCC. The VLCC unloads cargo in China, fill in ballast water tanks in order to maintain the required safe operation under various weather conditions by adjusting the trim while maintaining the optimum speed of the ship before it reach Kuwait port fully ballasted to reload cargo.

In this chapter, the outcome of the model has selected VLCC+BWTS5 (0.180) as the most feasible alternative for the VLCC. This outcome will be analysed using the sensitivity analysis of the criteria based on the changes of the relative importance of the criteria and sub-criteria in chapter-7.

6.1 The building of a hierarchy

The intention of the developed model is to help decision makers to select the most feasible BWTS for their ships by taking into account all the important identified criteria when selecting a Ballast Water Treatment System (BWTS). The ultimate goal of the developed AHP model is shown in Figure 6-1 which shows the goal on the left-hand side, i.e. select the most feasible BWTS alternative for the VLCC. The most feasible BWTS is meant to be the option which obviously satisfies by weighting more or scoring more against the identified criteria by considering both identified ballast water related criteria and ship related criteria. The global criteria are shown in the (2^{nd} level) to the right hand side of the ultimate goal, then sub-criteria or indicators to the right hand side of the global criteria are shown in the(3rd level), then sub sub-criteria are shown in (4th level) and the last level are the BWTS alternatives. The alternative contended of the VLCC tanker with each of the BWTS and denoted as (from VLCC+BWTS1 up to VLCC+BWTS7). Hence, each of the seven BWTS alternatives for the given VLCC are compared between each other against each criterion (or sub criterion), directly or indirectly, in order to achieve the ultimate goal of the model. It is worth noting that, the alternatives are not directly connected to the criteria in the 2nd level but to ones in the 3rd and lower level. Thus, the alternatives were assessed against each sub criterion and sub-sub criterion (level 3 & 4) in the AHP model.

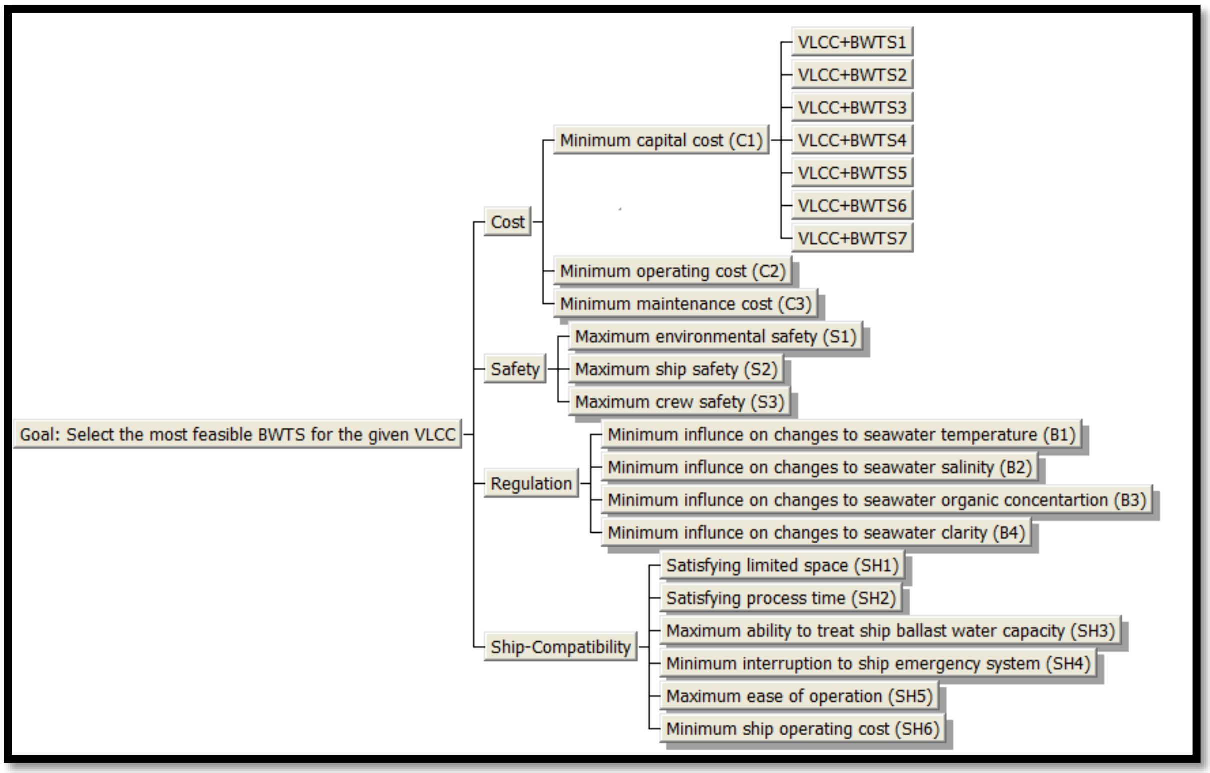

Figure 6-1: The hierarchy structure for this study, alternatives are shown connected for the Minimum capital cost criterion only.

For more information on the criteria or parameters considered by the model see Chapter 4, section 4.5 conclusions learned from the interviews. The detailed outcome from case study one using the developed decision support tool Figure 6-1 is presented next.

6.2 Case study

All the obtained results and calculations of the priority vectors using Microsoft Excel were presented in chapter 5. Based on the preferences obtained from a decision maker of this particular shipping company on each of the identified criteria in the model, input from the data of the VLCC particulars and its voyage data; finally inputs of the evaluations based on aggregated data of each BWTS alternatives. Synthesising inputs, the output or the outcome was obtained. It is worth noting that changes to any of these three inputs or the type of data used as inputs to the model to influence the output of the model will be checked in the next chapter.

The VLCC unloads cargo in China, and fills in ballast water tanks in order to maintain the required safe operation under various weather conditions by adjusting the trim while maintaining the optimum speed of the ship before it reaches Kuwait port fully ballasted. As we noted that during this leg, the VLCC steams for 14 days before reaching back to Kuwait in order to reload crude oil. The approximated average of high and low seawater temperatures difference between Kuwait and Huizhou as a geographic locations ports is 4˚C (i.e. 19˚C- 15˚C = 4˚C; average high seawater temperature difference between the two locations is 9.6˚C i.e. 32˚C - 22.4˚C = 9.6˚C). Due to the lack of data, it was assumed that salinity and organic concentration of the seawater has not significantly changed between the given ports.

The details of the obtained results are discussed in the sub sections below firstly.

6.2.1 Results obtained from the case study

6.2.1.1 Cost criterion

The comparison of the cost between the alternatives, was based on the minimum capital, operating and maintenance costs between each of the seven BWTS alternatives. Based on the calculated PV capital cost and operating cost of treating 600,000 tonnes of ballast water a year of each of the BWTS alternatives is discussed in chapter 5. BWTS3 alternative appeared to be the lowest value amongst the given alternatives. This is expected because BWTS3 alternative has satisfied or scored more for the minimum capital and operating cost criteria as shown on the graph in Figure 6-2. However, based on the subjective maintenance cost criterion, BWTS3 alternative has scored the highest risk towards the minimum maintenance cost criterion. On the other hand, BWTS1&, 4-7 equally scored lower risk towards the minimum maintenance cost criterion and thus were preferred or scored more than the rest of the BWTS alternatives as shown on the graph in Figure 6-2.

The decision maker prioritised all the cost sub-criteria as equally important and that meant any of the defects between the alternatives about each of these sub-criteria are equally important to the decision maker. Therefore, by combining all these facts in, Figure 6- 2, along with the priorities obtained from the decision maker about the importance of each of the cost indicators the result is obtained and shown in Figure 6- 3.

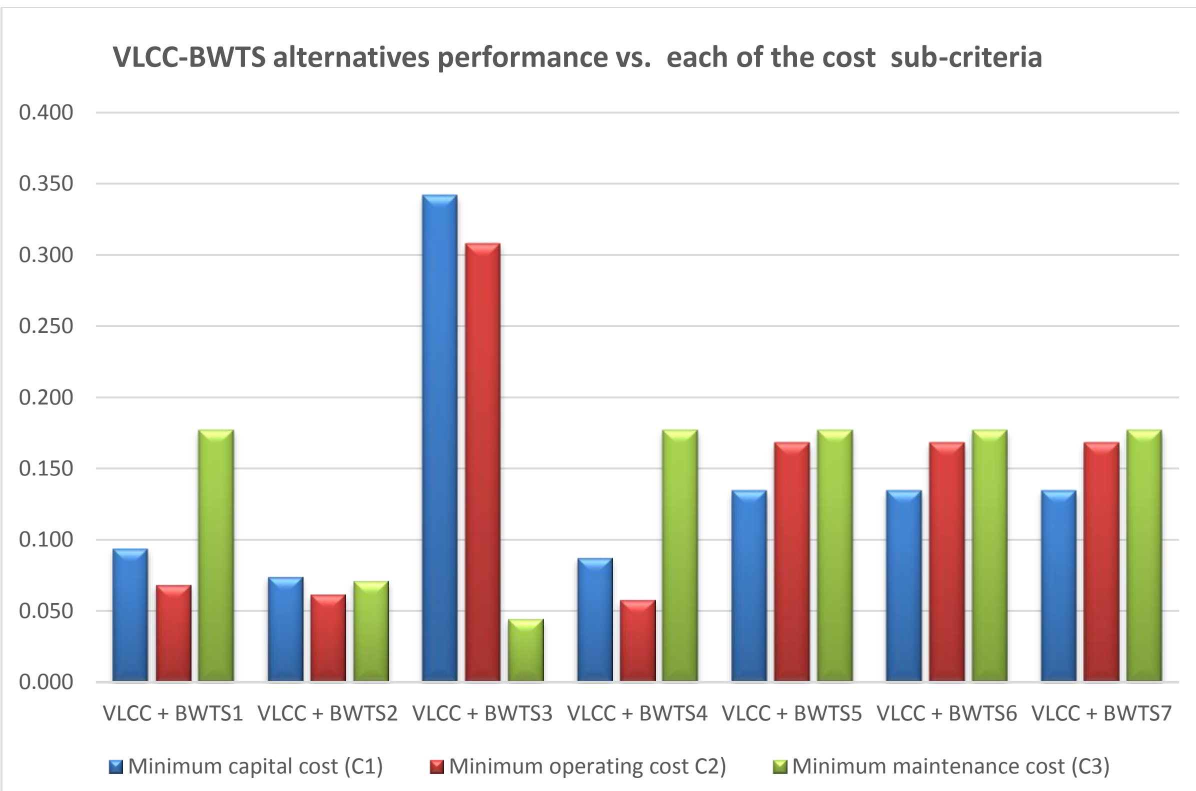

Figure 6-2: VLCC+BWTS alternatives performance vs. the cost sub-criteria

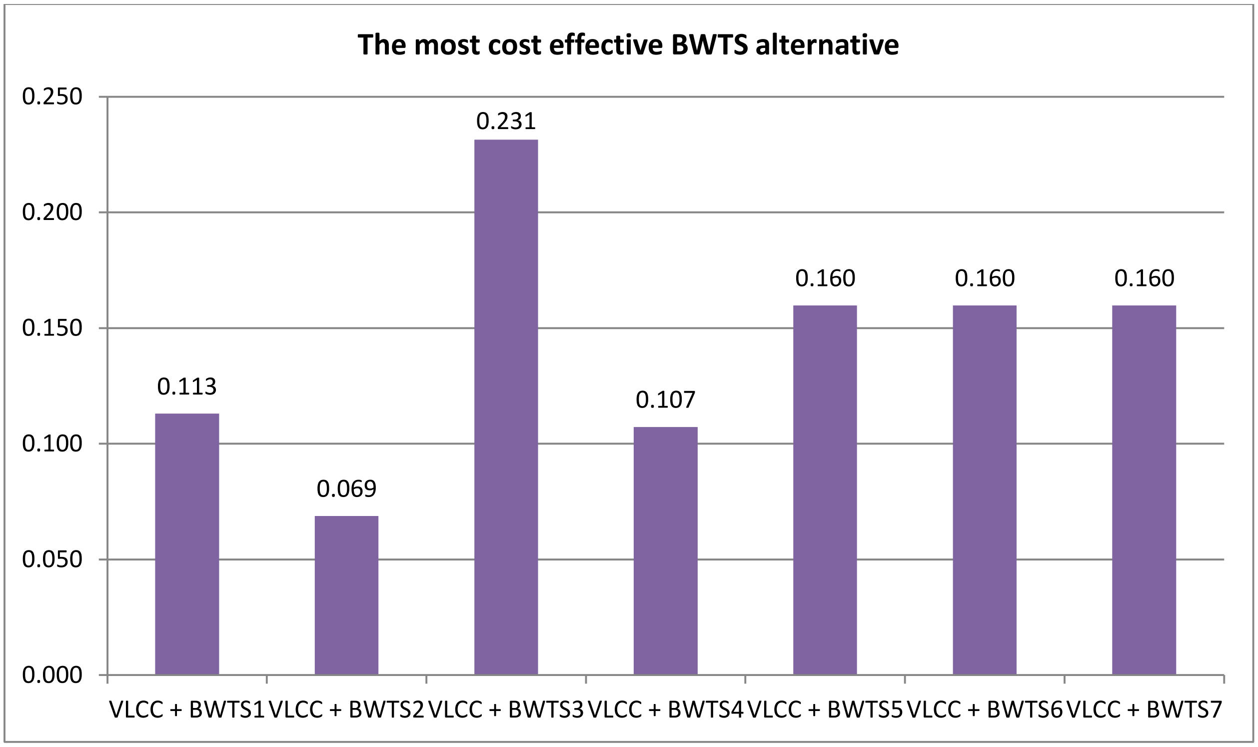

Figure 6-3: The alternatives order after combining decision maker's importance for cost criterion

In Figure 6-3, VLCC+ BWTS3 alternative is shown as the most preferred alternative (0.231) for the given VLCC. This is because VLCC+BWTS3, has scored more (or weighted way more) than other alternatives by its capital and operating cost criteria that has increased its success to be selected than any other alternative.

On the other hand, VLCC+ BWTS5-7 alternatives have also been shown equally as the 2nd preferred alternatives (0.160) for the given VLCC to satisfy the minimum cost criterion based on the preference given by the decision maker to satisfy the cost criterion.

6.2.1.2 Safety criterion

Please note that the same comparison procedures between the alternatives as discussed in the cost criterion evaluations are followed for each identified criterion in the model. The comparison between the safety of the alternatives which was based on the maximum environmental, ship and crew safety between each of the seven BWTS alternatives. Based on the subjective environmental safety risk criterion, VLCC+ BWTS1& 5-7 alternatives were found the least risky to the environmental safety criterion. This has been shown by the result obtained in Figure 6-4. On the other hand, VLCC+ BWTS1 alternative is shown as the safest alternative to the VLCC amongst all alternatives because of its unique anti corrosion advantage to ballast tanks. It was also noted that BWTS1 is equally safe in terms of crew safety with BWTS5-7 alternatives as shown in Figure 6-4.

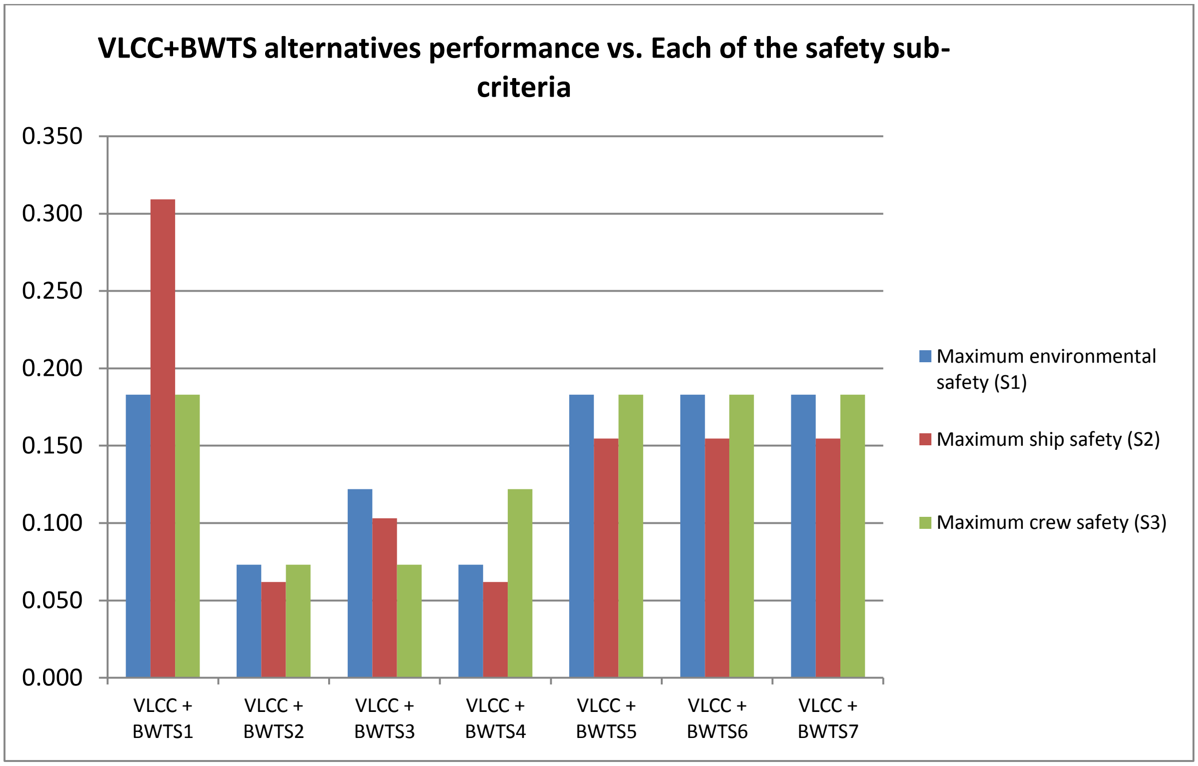

Figure 6-4: VLCC+BWTS alternatives performance vs. the safety sub-criteria

The decision maker prioritised all the safety sub-criteria to be equally important which meant that any of the defects between the alternatives about each of these sub-criteria would score as a very important aspect to the decision maker. Therefore, by combining all these facts in Figure 6-4, along with the priorities obtained from the decision maker about the importance of each of the cost indicators are obtained and the result is shown on the graph in Figure 6-5.

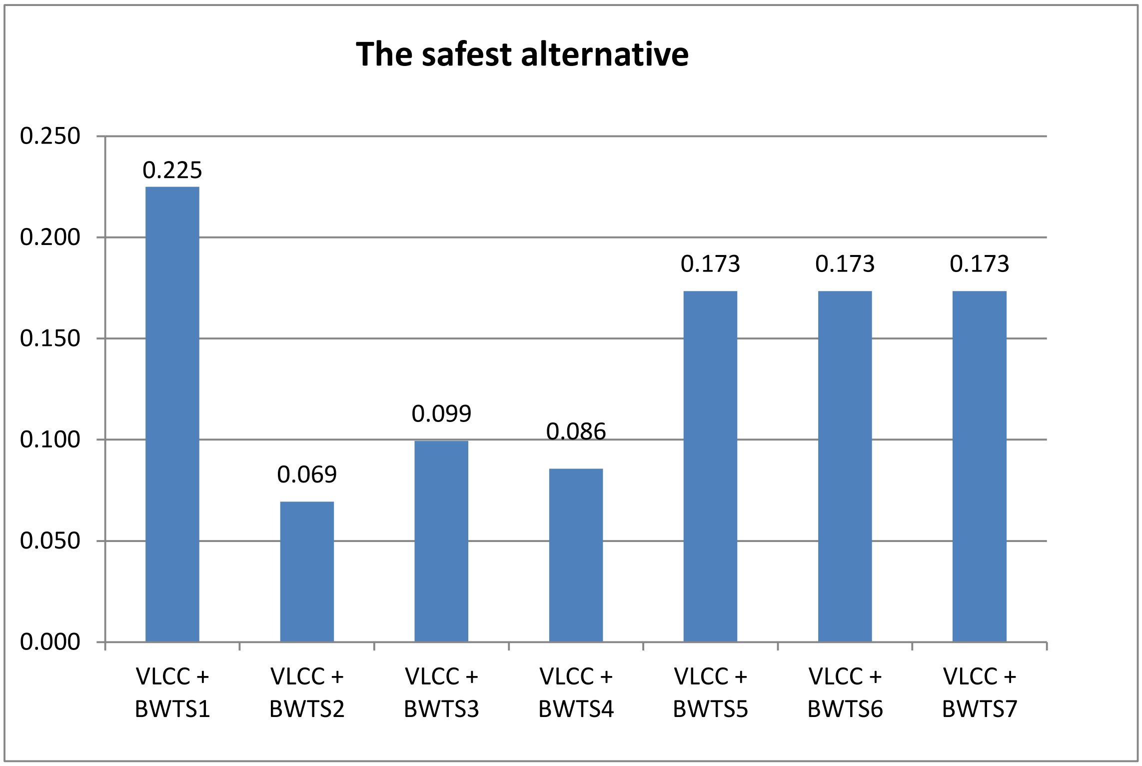

Figure 6-5: The alternatives order after combining decision maker's importance for the safety criterion

In Figure 6-5 the VLCC+BWTS1 alternative is found as the most preferred alternative (0.225) for the given VLCC if the safety criterion is considered alone. On the other hand, BWTS5-7 alternatives (0.173) equally have also been shown as the 2nd alternatives, after the VLCC+BWTS1, as the preferred alternatives for the given VLCC to satisfy the safety criterion according to the evaluations (preferences) obtained by the decision maker of the VLCC. It should be noted that, all BWTS alternatives are safe as this is a critical condition by IMO for any BWTS, however, what is shown in graph Figure 6-5 is that VLCC+BWTS1 alternative is safer than other alternatives.

6.2.1.3 Regulation criterion

The comparison of the regulation (or bio-efficacy) criterion between the alternatives was based on the risks to the influence on changes of the seawater temperature, salinity, organic concentration and clarity on bio efficacy between each of the seven BWTS alternatives.

Based on the subjective aggregated information from the literature review of relevant studies as discussed in chapter 5, the result obtained is shown in Figure 6-6. VLCC+BWTS5-7 alternatives were equally shown as the most preferred alternatives for both the change on seawater temperature, salinity and organic concentration. However, they were found to be the least preferred options if seawater clarity risk issue. On the other hand, VLCC+BWTS1 alternative is also shown as a preferred option for salinity of seawater change risk criterion.

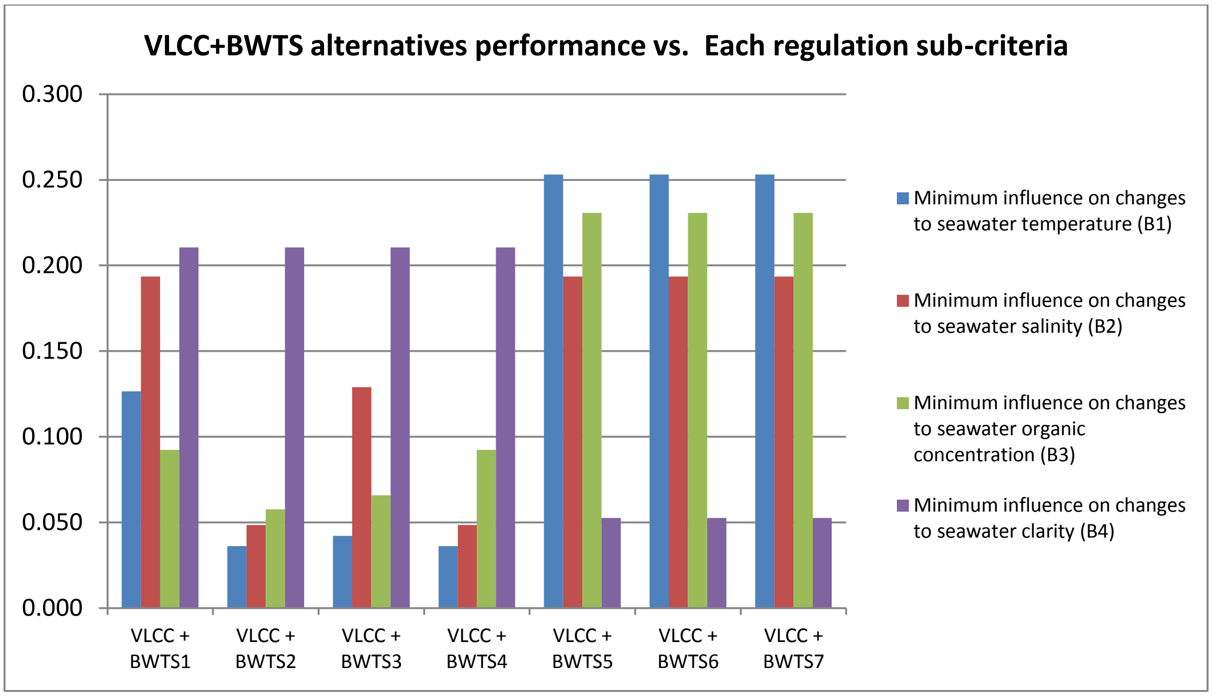

Figure 6-6: VLCC+BWTS alternatives performance vs. Each of the regulation sub-criteria

By combining all these facts in Figure 6-6, along with the priorities obtained from the decision maker about the importance of each of the regulation indicators, the result was obtained and shown on the graph in Figure 6-7.

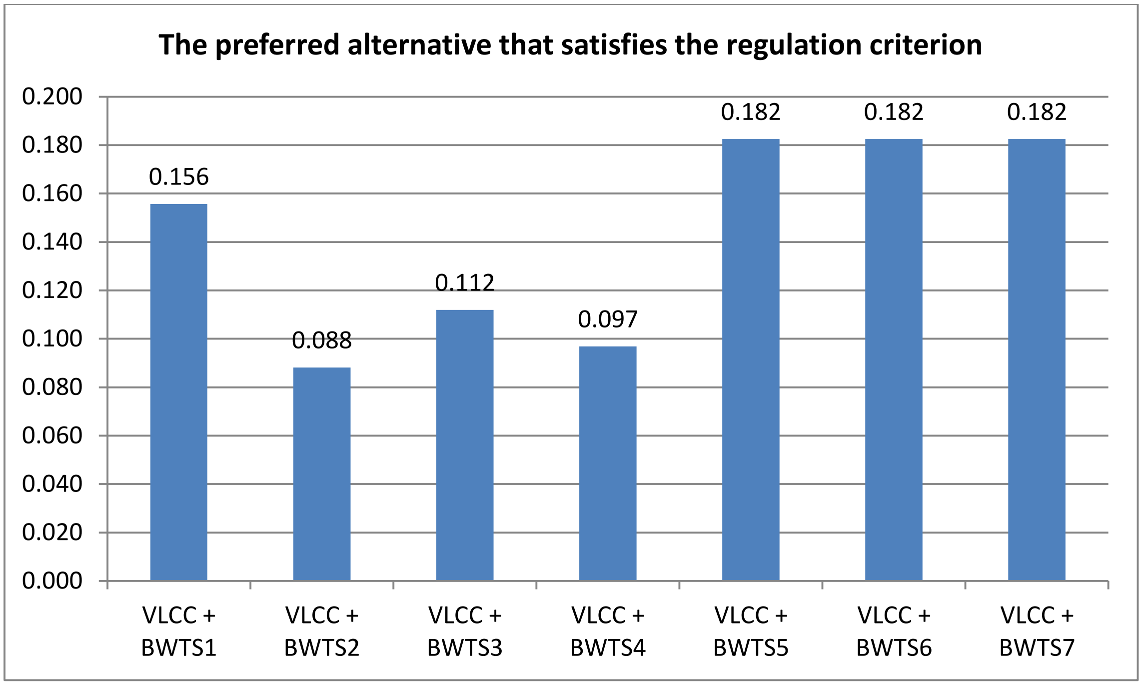

Figure 6-7: The alternatives order after combining the regulation sub-criteria

In Figure 6-7 the VLCC+BWTS5-7 alternatives are equally shown as the most preferred alternatives (0.182) for the given VLCC if the regulation criterion was only considered. This is because BWTS5-7, were equally less affected by changes in seawater temperature, salinity and chemical property change criteria. These have scored (weighted) more for these BWTS alternative more than the rest of the given alternatives. On the other hand, VLCC+BWTS1 have also been shown as the second preferred alternative (0.156) for the given VLCC to satisfy the regulation criterion.

It is important to remember that all these BWTS alternatives are approved by their administration and also by IMO when proper and some also have got the USCG approval. However, due to the differences of standards between different regions, the model chosen to evaluate, from a feasibility point of view, their ability to satisfy the regulation criterion through satisfying the indicators or sub-criteria identified by the model.

6.2.1.4 Ship compatibility

The comparison of the ship compatibility criterion between the alternatives was based on the ship compatibility's sub-criteria or indicators:

1. Satisfying limited space (SH1)
    a. Compact as one unit (SH1-A)
    b. Can be installed in a hazardous place (SH1-B)
    c. Minimum requirement to additional equipment (SH1-C)
2. Satisfying process time (SH2)
    a. Satisfy ship operating mode (SH2-A)
    b. Satisfy ship voyage length, for 14 & 24 days (SH2-B)
3. Maximum ability to treat ship ballast water capacity (SH3)
4. Minimum interruption to ship emergency system (SH4)
5. Maximum ease of operation (SH5)
6. Minimum Ship operating cost (SH6)
    a. Minimum requirement for extra expertise (SH6-A)
    b. Minimum requirement for crew training (SH6-B)
    c. Minimum fuel consumption (SH6-C)
    d. Maximum ease for maintenance (SH6-D)

All the above criteria combined are defined to evaluate the ship compatibility between each of the seven BWTS alternatives are shown on the graph in Figure 6-8 and are summarised below:

- VLCC+BWTS3 alternative (0.186) is the most preferred alternative to minim ship operating cost.
- VLCC+ BWTS5-7 (the UV ballast water treatment systems) alternatives are the most preferred alternatives to both minimum interruption at ship emergency criterion (0.241) and satisfying process time criterion (0.233).
- VLCC+ BWTS1& 2 alternatives weighted less amongst other alternatives towards the maximum ease of operation criterion (0.100).

- VLCC+ BWTS3, 4 &5 alternatives are the most preferred alternatives towards the maximum ability to treat ship ballast water capacity (0.180).
- VLCC+BWTS1 alternative is the most preferred alternative to satisfy limited space criterion (0.195).

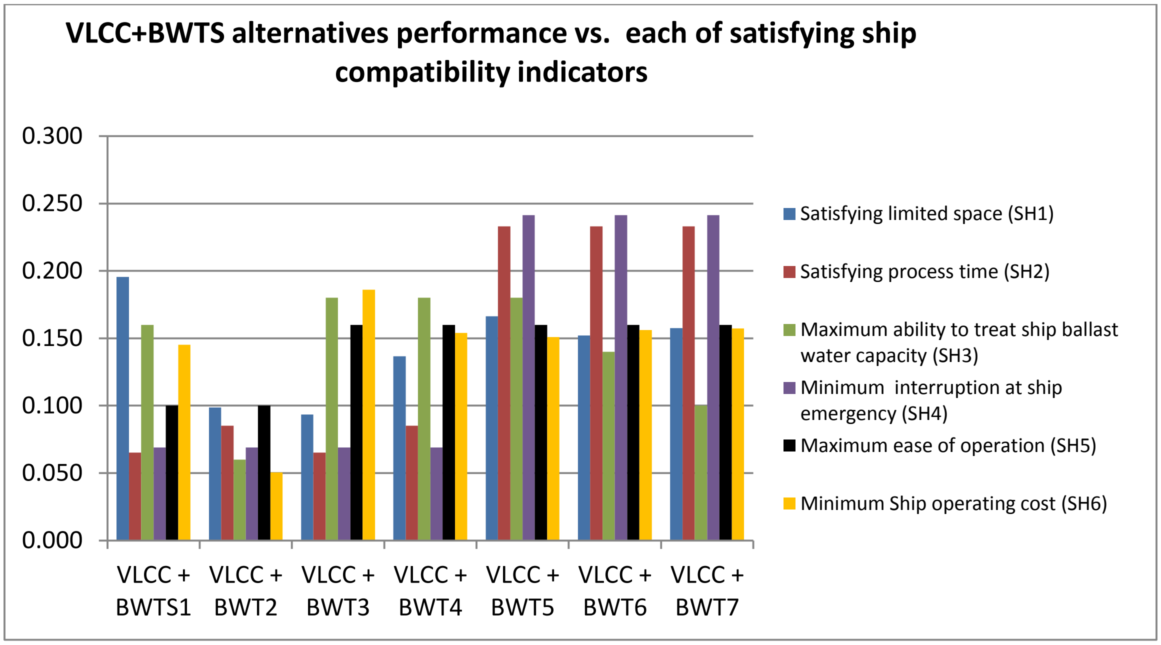

Figure 6-8: VLCC+BWTS alternatives performance vs. each of satisfying ship compatibility sub-criteria

The decision maker prioritised the minimum ship operating cost sub-criterion as the most important criterion. After that, the maximum ability to treat ship ballast water capacity criterion and the minimum interruption at ship emergency criteria were equally more prioritised than the rest of criteria. Therefore, by combining all the facts from the graph in Figure 6-8, alongside with the decision maker's priorities or preferences the importance of the ship compatibility's indicators are shown on the graph in Figure 6-9.

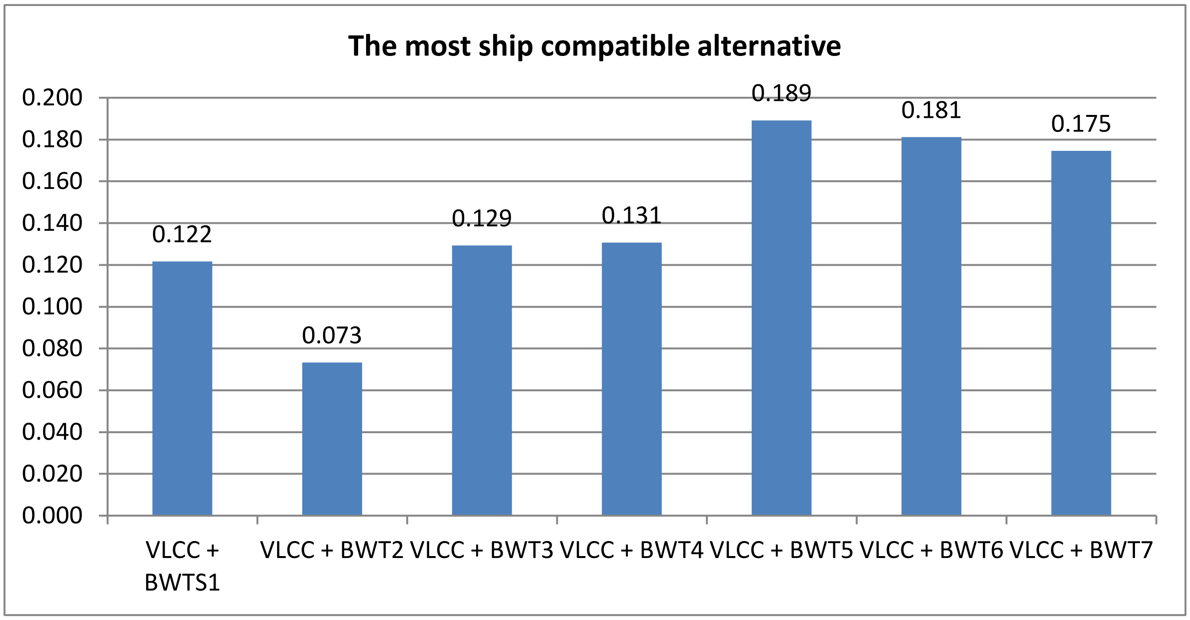

Figure 6-9: The alternatives order after combining decision maker's importance for ship compatibility criterion.

In Figure 6-9, VLCC+BWTS5 is shown as the most preferred alternative (0.189) for the VLCC based on the decision makers input preferences. This is because VLCC+BWTS5 alternative has scored more than any of the given alternatives with regards to the satisfying limited space and the maximum ability to treat ship ballast water capacity criteria amongst all the given alternatives. In addition, VLCC+BWTS5 alternative has equally satisfied the minimum interruption at ship emergency and satisfying process time criteria as VLCC+BWTS6&7 alternatives. However, VLCC+BWTS5 alternative scored negligibly less at satisfying the minimum ship operating cost than VLCC+BWTS6&7 alternatives. Based on combining all these scores the model selected VLCC+ BWTS5 over the rest of the given alternatives.

Next sub sections, more details of how results were obtained about the sub-criteria for the ship compatibility are presented.

6.2.1.4.1 Satisfying limited space (SH1)

The comparison of the limited space criterion between the alternatives was based on satisfying three indicators or criteria:

- The compact as one unit (SH1-A) criterion,
- Can be installed in a hazardous place (SH1-B) criterion, and
- The minimum requirement to additional equipment (SH1-C) between the seven BWTS alternatives.

The evaluations of both, the compact as one unit and fitting into hazardous place were subjectively evaluated and the minimum requirement to additional equipment is objectively evaluated for all the seven alternatives as presented and discussed in chapter 5. The result derived is shown on the graph in Figure 6-10.

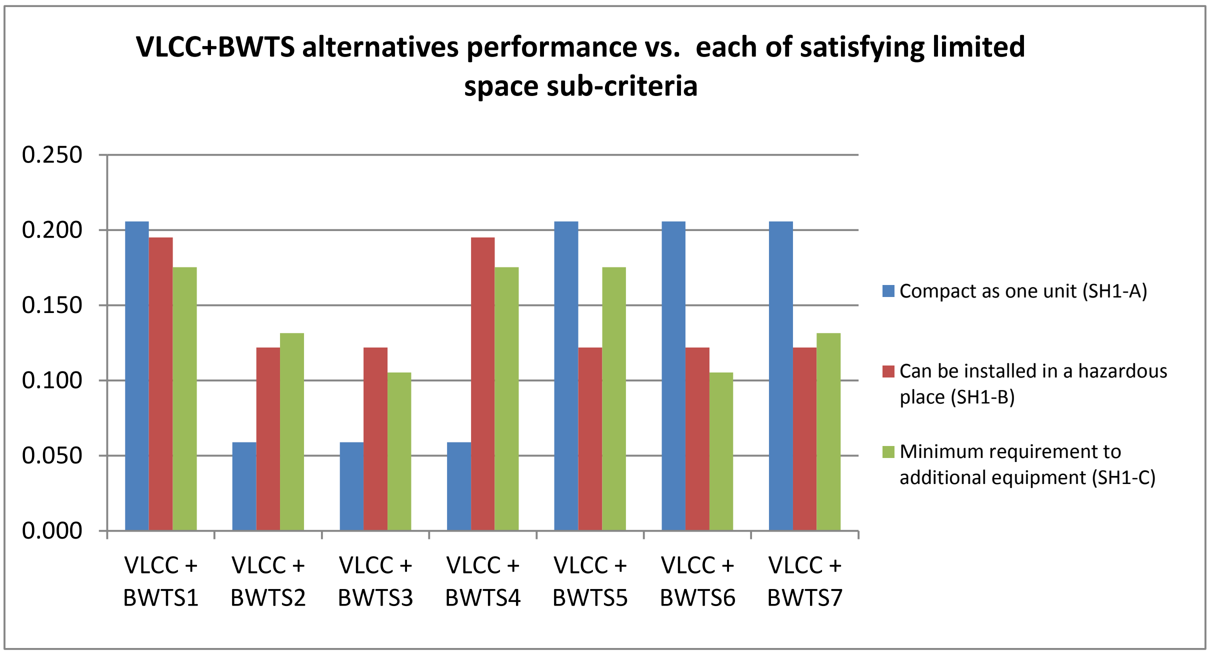

Figure 6-10: VLCC+BWTS alternatives performance vs. each of satisfying limited space sub-criteria

VLCC+BWTS1& 5-7 equally (0.206) are shown as the most preferred options to satisfy the compact as one unit criterion as expected. This is because these alternatives required fewer components and thus were found to be more compact systems. On the other hand,VLCC+BWTS1&4 alternatives were equally (0.195) found as the most preferred alternatives to satisfy the hazardous place as they scored less to fire or crew hazard risks which other given alternatives may have.

Finally, based on the number of equipment of each alternative, VLCC+BWTS1, 4&5 alternatives (0.175) have been identified as the most preferred alternatives to satisfy the minimum requirement to additional equipment amongst the other alternatives as expected. Because those alternatives had less equipment than other alternatives according to the vendor's information.

The decision maker have prioritised both, the compact as one unit criterion and the can be installed in a hazardous place criterion as the most important criteria. Therefore, by combining all these facts in Figure 6-10, alongside with the priorities by the decision maker, the results are shown on the graph in Figure 6-11.

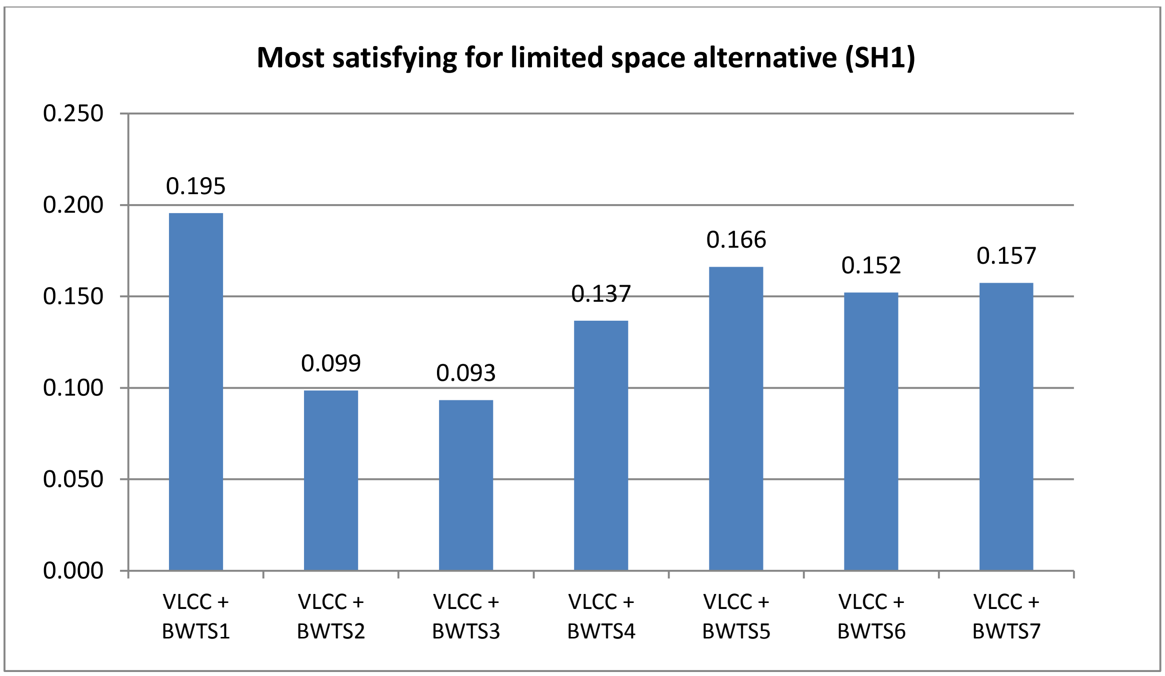

Figure 6-11: The alternatives order after combining decision maker's importance for satisfying the limited space criterion.

It is very clear from the graph in Figure 6-11 that BWTS1 alternative (0.195) is the most preferred alternative for the given VLCC as expected. This is because BWTS1 alternative has equally scored for the compact as one unit criterion as well as BWTS5-7 alternatives. In addition, both BWTS1&4 alternatives equally scored the highest amongst the given alternatives toward the can be installed in a hazardous place criterion. Finally BWTS1 alternative has also equally scored for the minimum requirement to additional equipment criterion as well as BWTS4&5 alternatives.

6.2.1.4.2 Satisfying process time (SH2)

Satisfying process time criterion between the alternatives was based on satisfying the ship operating mode and satisfying ship voyage length sub-criteria between each of the seven BWTS alternatives.

Based on the literature review of relevant studies on the process time of each type of disinfection treatment and process time is presented in chapter 5. The derived result is shown on the graph in Figure 6-12. VLCC+BWTS5-7 are shown equally as the most preferred alternatives to score the highest on both ship operating mode and voyage length criteria (0.241), (0.200) respectively as expected. Because, VLCC+BWTS5-7 disinfection has been found, according to the aggregated information chapter 5, to be shortest process time amongst the given alternatives. Therefore, VLCC was assumed to be tight to a time charter for delivering the consignments between the loading area i.e. Kuwait to unloading area i.e. China. These alternatives will enable the VLCC to fulfil demands in short notice and secure business.

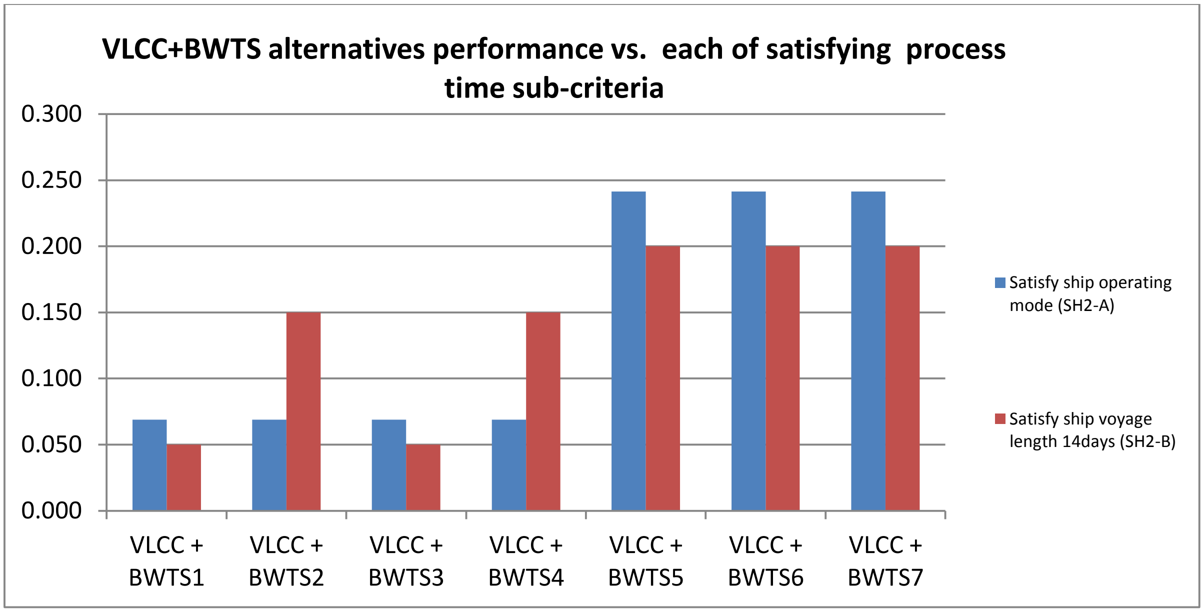

Figure 6-12: VLCC+BWTS alternatives performance vs. each of the satisfying process time sub-criteria, voyage length is 14 days

On the other hand, the alternatives are required to effectively satisfy the VLCC voyage duration which takes 14 days between the two regions. Based on the subjective evaluation of the length of each alternative process time, it was evaluated that VLCC+BWTS5-7 alternatives with their short process time scored more than any other alternatives to satisfy such voyage length criterion. VLCC+BWTS 2 &4 alternatives were also evaluated to be able to satisfy such a ship length but not effective as VLCC+BWTS5-7 thus scored less. The rest of the alternatives will require longer process time in order to satisfy the VLCC voyage length.

It is worth noting that the decision maker have prioritised ship operating mode criterion way more than satisfying ship voyage length criterion. Therefore, by combining all these facts in, Figure 6-12, alongside with the priorities obtained from the decision maker about the importance of each of the satisfying limited space indicators, the result is obtained and shown in Figure 6-13.

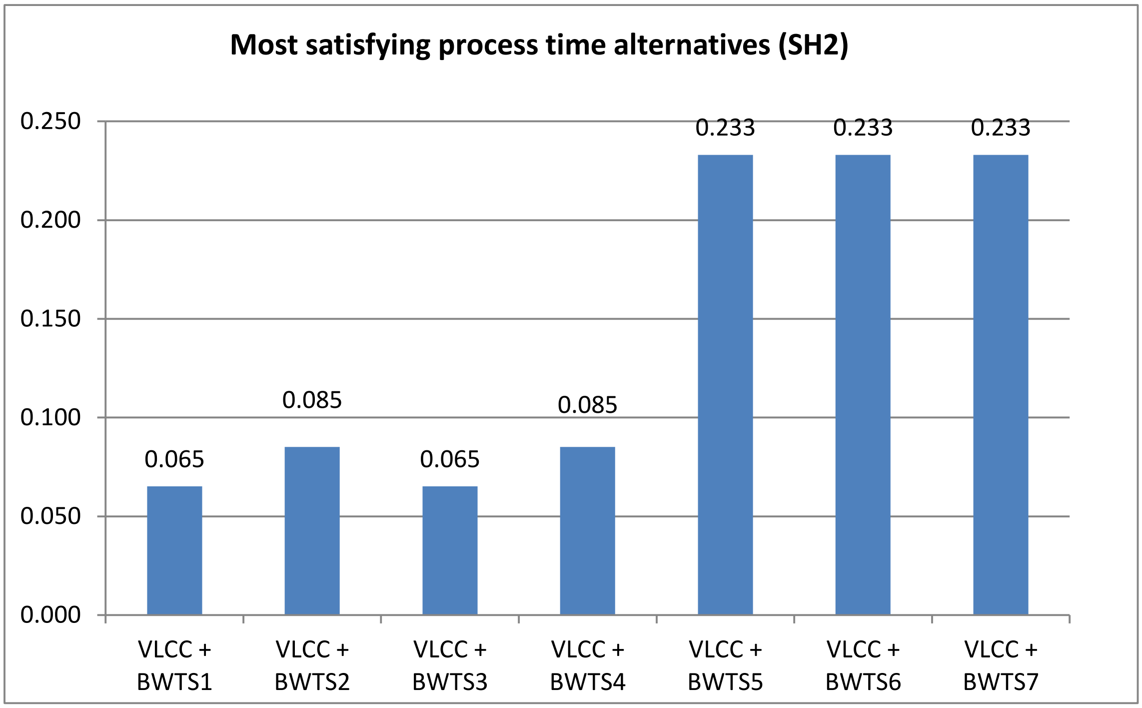

Figure 6-13: The alternatives order after combining decision maker's importance for satisfying the process time criterion.

In Figure 6-13, BWTS5-7 alternatives have been equally shown as the most preferred alternatives (0.233) for the given VLCC to satisfy the process time criterion (SH2). This was expected as these alternatives presented less process time and showed to be more suitable for the ship operating mode.

6.2.1.4.3 Minimum Ship operating cost (SH6)

Comparing the minimum ship operating cost criterion between the alternatives was based on satisfying the minimum requirement for extra expertise (SH6-A); minimum requirement for crew training (SH6-B); minimum fuel consumption (SH6-C); maximum ease for maintenance (SH6-D) sub-criteria between each of the seven BWTS alternatives. The derived results are shown in Figure 6-14.

Based on the approximated fuel consumption in chapter 5, VLCC+BWTS3 alternative (0.580) is the most preferred option for the minimum fuel consumption amongst other alternatives as expected. The second preferred alternative is VLCC+BWTS4 (0.122).

However, VLCC+BWTS3 weighted less than the other identified criteria such as the maximum ease of maintenance, minimum crew training and minimum requirement for extra expertise. On the other hand, VLCC+BWTS5, 6 &7 are equally found the most preferred alternatives in criteria (0.211) such as the maximum ease of maintenance, minimum crew training and minimum requirement for extra expertise. However, VLCC+BWTS5, 6 &7 alternatives with little differences (0.034), (0.053) & (0.058) receptively have all weighted less toward the minimum fuel consumption as expected of a UV ballast water treatment.

On the other hand VLCC+BWTS1 alternative weighted similar to VLCC+BWTS5-7 alternatives in criteria such as minimum crew training and minimum requirement for extra expertise. VLCC+BWTS1 alternative have also weighted more than VLCC+BWTS5-7 alternatives in the minimum fuel consumption criterion. However, VLCC+BWTS1 alternative is less preferred in maximum ease for maintenance criterion.

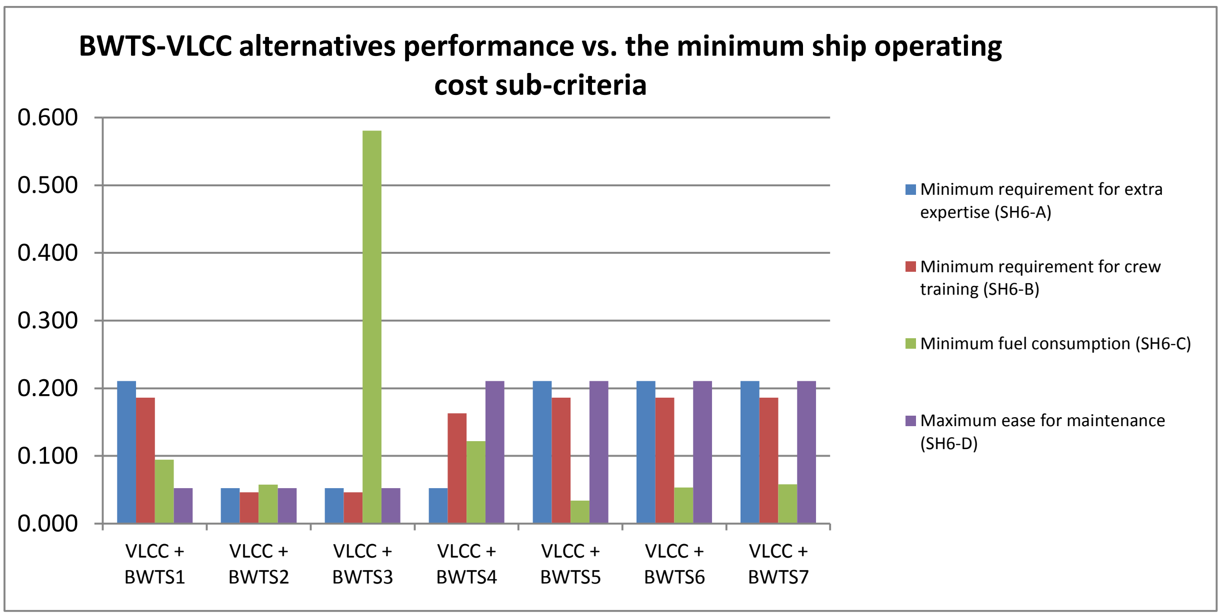

Figure 6-14: VLCC+BWTS alternatives performance vs. each of the minimum ship operating cost indicators, voyage length is 14 days

It is worth noting that the decision maker prioritised the minimum fuel consumption criterion more than any other criteria. Next he prioritised the maximum ease for maintenance criterion more than the minimum requirement for crew training criterion. The least important criterion was the minimum requirement for extra expertise.

Therefore, by combining all these facts in, Figure 6-14, alongside with the priorities obtained from the decision maker about the importance of each of the satisfying limited space indicators, the result is obtained and shown in Figure 6-15.

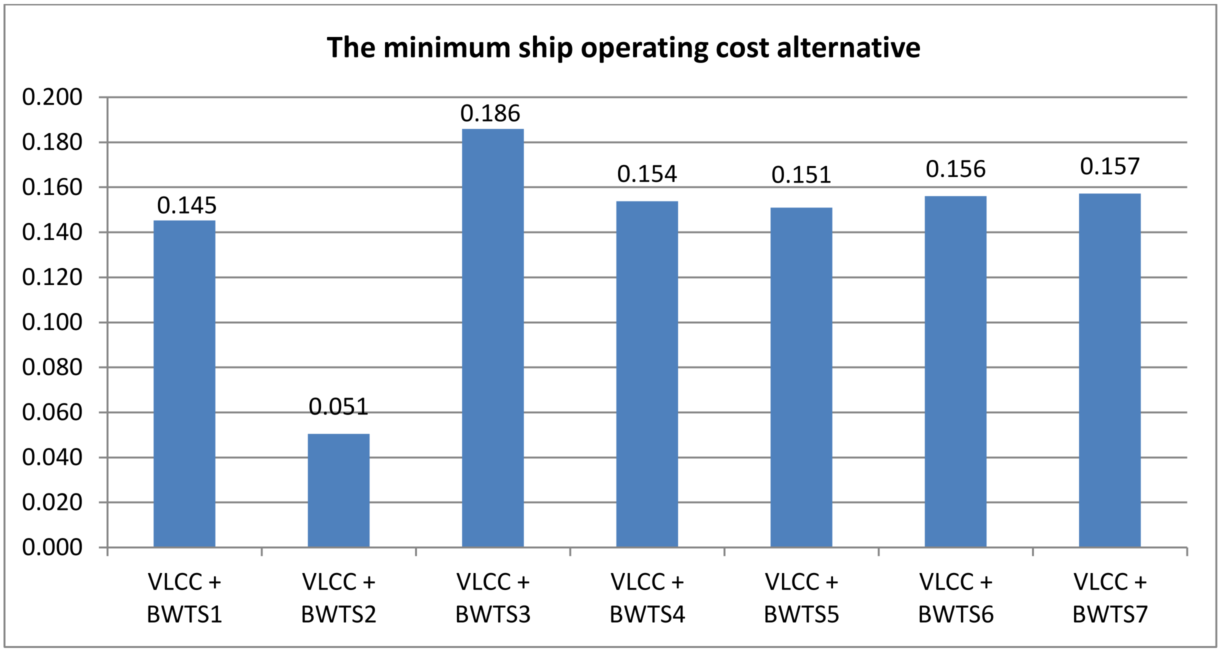

Figure 6-15: The alternatives order after combining decision maker's importance for minimum ship operating cost criterion.

In Figure 6-15, VLCC+BWTS3 alternative (0.186) has been shown as the most feasible alternative for the given VLCC after synthesising the preference from the decision maker to satisfy the minimum ship operating cost criterion. This was expected because VLCC+BWTS3 alternative was found to be the most fuel consumption efficient alternative as well as this criterion was highly prioritised by the decision maker. VLCC+BWTS7 alternative (0.157) scored more than VLCC+BWTS5&6 alternatives and therefore was shown as the next preferred alternative after VLCC+BWTS3 for the given VLCC as expected.

6.2.1.5 Aggregation of the outcomes based on the detailed weights of developed decision support tool

Comparing between the seven alternatives was based on combining three inputs, as discussed earlier in this chapter, namely:

1. Inputs from the decision maker through his evaluations to the relative important of each identified criteria in the model;
2. Inputs from the VLCC particulars and voyage data;
3. Finally, inputs from technical data aggregated about each BWTS alternative.

Synthesising the three inputs above, the combined vectors for satisfying the global criteria between each of the seven BWTS alternatives are shown on the graph in Figure 6-16.

All the above combined criteria are defined to evaluate each of the seven BWTS alternatives against the global criteria are shown on the graph in Figure 6-16 as expected and summarised below:

- VLCC+BWTS1 alternative (0.225) is the most preferred alternative to both the safety and the regulation criteria.
- VLCC+BWTS3 alternative (0.231) is the most preferred alternative to the cost criterion.
- VLCC+BWTS5 alternative (0.189) equally is the most preferred alternatives to the ship compatibility criterion.
- VLCC+BWTS5-7 alternatives (0.182) equally are the most preferred alternatives for the regulation criterion.

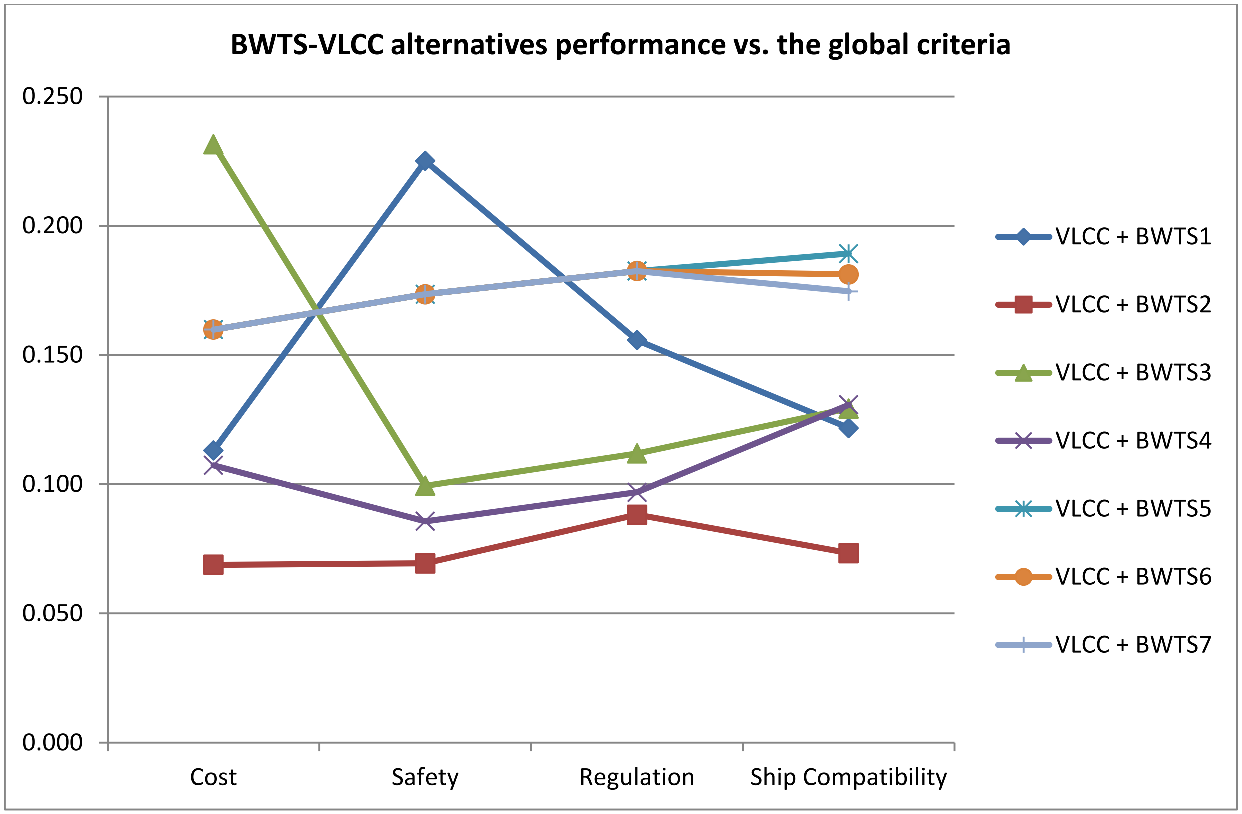

Figure 6-16: BWTS-VLCC alternatives performance vs. the global criteria, case study one

The decision maker prioritised the regulation criterion more than the rest of the other global criteria. Next he prioritised the safety criterion more than the ship compatibility criterion. Interestingly, the least important criterion to this particular decision maker was the cost in this case study. Therefore, by combining all of these facts on the graph in Figure 6-16 alongside with the priorities obtained from the decision maker the results are shown on the graph in Figure 6-17.

Clearly, from Figure 6-17, VLCC+BWTS5 alternative (0.180) has been selected by the model as the most feasible alternative for the given VLCC as expected. This is because although VLCC+BWTS3 alternative scored or performed best under the cost criterion, it scored way less than other alternatives for safety, regulation and ship compatibility criteria. VLCC+BWTS1 alternative has also scored or performed best under the safety criterion, it scored way less than other alternatives on cost, regulation, and ship compatibility criteria. On the other hand, VLCC+BWTS5 alternative has scored or performed equally as well as with VLCC+BWTS6&7 for the cost (0.160), safety (0.173) and regulation (0.182) criteria. In addition, VLCC+BWTS5 alternative surpassed both VLCC+BWTS6&7 and scored higher towards the ship compatibility criterion (0.189).

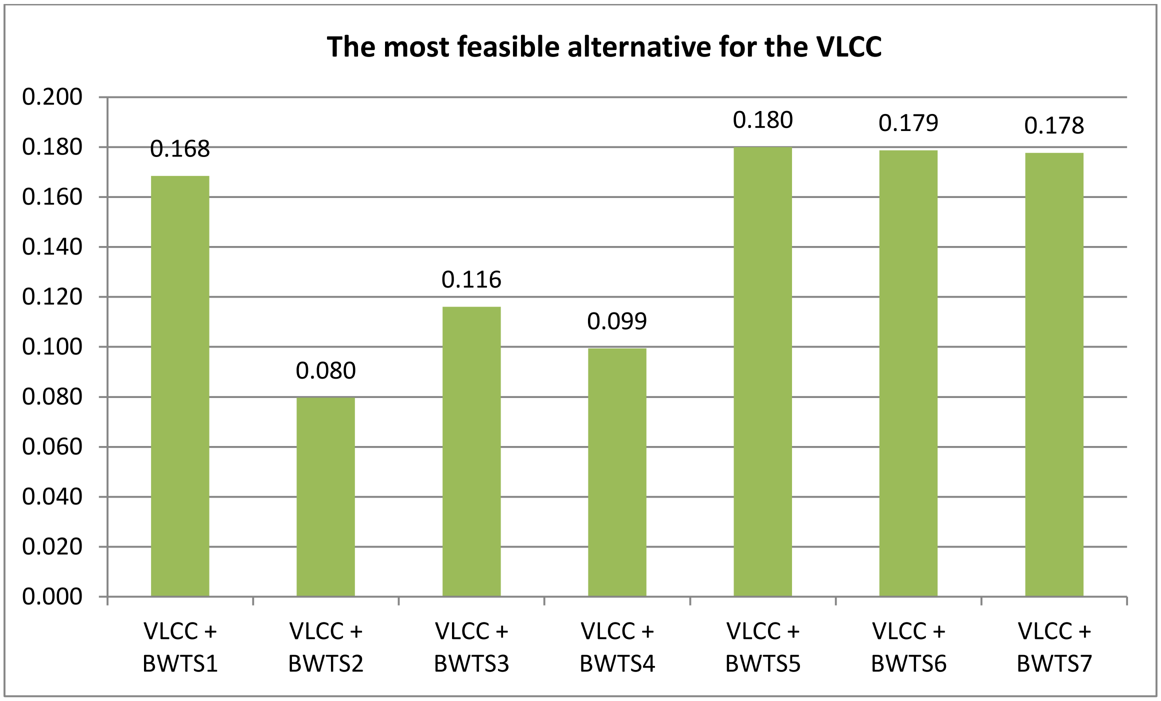

Figure 6-17: The alternatives order after combining decision maker's importance global criteria in case study one

On the other hand, VLCC+BWTS1 alternative (0.168) has been shown as the fourth feasible alternative after the three VLCC+BWTS5-7 alternatives. This is expected because VLCC+BWTS1 alternative performed or scored less than VLCC+BWTS5-7 alternatives under cost, regulation, and ship compatibility. On the other hand, VLCC+BWTS1 alternative performed or scored better than VLCC+BWTS2-4 alternatives under the safety, regulation, and ship compatibility criteria.

6.3 Conclusions

In this chapter, the derived outcome by using the decision support tool are presented and discussed in detail. It is important to note that there was no surprises detected by the user based on the data inputs to the model. In other words, the model developer find that the model performance is reasonable and it is working as expected. For example, the comparison between the seven alternatives, the model was able to identify the best alternative against each identified criterion, and this was very clear from the obtained graphs presented in this chapter.

The model was also able to evaluate and detect the performances of each BWTS alternative against each parameter and thus making the decision much simpler through the graphs. In addition, it was also able to present the other possible alternatives and their potentials as other alternatives for the given VLCC.

Because some data inputs to the model were based on a second hand sources, subjective and approximated data, uncertainties may rise for different reasons. Therefore, it is important to understand how the developed decision support tool would behave if the decision maker has changed his preferences towards the identified criteria or due to a change in future plans. This raises the following questions: How can we test the validity and the applicability of the developed decision tool? How can we gain more understanding and be more confident about the results? Why this model used in this thesis is valid? Why the developed decision support tool is valid? And finally why the outcome presented in this chapter is valid? Answering these questions will validate the applicability and the validity of the developed model.

Chapter 7 will discuss sensitivity analysis, applicability and validation to the developed model.

Chapter 7: Developed Model Sensitivity Analysis, Applicability and Validation

7.0 Introduction

The result derived from the model or tool has selected VLCC+BWTS5 alternative (0.180) as the most feasible alternative for the given VLCC. Because some data inputs to the model were based on a second hand source, subjective, and approximated data, uncertainties may rise for different reasons. The aim of this chapter is:

1. To analyse the outcome of the developed model through performing sensitivity analysis of the criteria based on the changes of the relative importance of the identified criteria and sub-criteria in order to find out which of these criteria are important and need to be carefully considered by the decision maker.
2. To investigate the findings from the sensitivity analysis in a proper case study in order to confirm the tool's applicability.
3. To validate the developed decision support tool and its outcome.

In order to assess and analyse the derived outcome it is proper to perform the sensitivity of the results by the model. The sensitivity analysis is discussed next in more details.

7.1 Sensitivity analysis

The sensitivity analysis is performed based on the changes of the relative importance of criteria and sub-criteria in order to find out which of them are critical and need to be carefully considered form the decision's maker point of view.

The AHP vectors of priorities which were acquired from Microsoft Excel calculations have been edited directly into the Expert Choice software to facilitate the sensitivity analysis build in this software. After synthesising the weights with respect to the ultimate goal i.e. to select the most feasible BWTS alternative for the VLCC, the derived results are shown in Table 7-1. Table 7-1 has shown that there is very small percent of differences between the derived results of both mathematical software that reached a maximum of 6% for the score given to VLCC + BWTS4. This difference is due to the reason that there is no single correct way to normalise a mathematical matrix in MCDM models. This is because there are many ways to calculate relative scores or weights which include simple averaging, geometric mean etc. (Olson, 1996). For example, Saaty (1980, p19), highlighted four different ways of normalising a given matrix to compute vector of priorities namely: (1) crudest, (2) better, (3) good, and (4) good. Saaty (1980), illustrated that these methods i.e.,1-4, provided small percentage of differences in the vector of priorities when applied as normalising methods to one particular matrix. The latter findings by Saaty (1980), implies that these small differences in the outcome between the two mathematical models i.e. Microsoft Excel and Expert Choice software cannot and should not be interpreted as errors of the derived outcomes, but should be considered as a normal consequence of employing a method of normalising a mathematical matrix between the two as confirmed by Saaty (1980). In this study, the Microsoft Excel mathematical model applied method (3) as suggested by Saaty (1980) for the computation of the vector of priorities which is the key difference from the unknown method employed by the Expert Choice software.

A clear evidence of the argument above can be realised from the outcomes of the selected BWTS alternatives by both mathematical models:

- The most feasible BWTS alternative is still the same one in both models,
- The least preferred BWTS alternative is still the same one in both models,
- VLCC+BWTS5-7 alternatives are still the same promising alternatives as indicated by both models.
- VLCC+BWTS1 is still the fourth promising alternative as indicated by both models.

The question is whether or not this error is serious one i.e. given unexpected outcome, or selecting the least preferred alternative as the best one etc. then this can be considered a very serious error. However, as shown in Table 7-1, the order and the selected alternatives are unchanged, and thus justified our view that this percentage of difference is not a serious one. Also this has justified the reliability of the results obtained by the two mathematical models i.e. the Microsoft Excel and the Expert Choice software.

Table 7-1: differences of the synthesised outcomes by Microsoft Excel versus Expert Choice for the alternatives

Alternatives (Ship + BWTS)	Outcome scores obtained by Microsoft Excel	Outcome scores obtained by Expert Choice	Percent of difference
VLCC + BWTS1	0.168	0.165	**-2%**
VLCC + BWTS2	0.080	0.084	**5%**
VLCC + BWTS3	0.116	0.117	**1%**
VLCC + BWTS4	0.099	0.105	**6%**
VLCC + BWTS5	0.180	0.178	**-1%**
VLCC + BWTS6	0.179	0.176	**-2%**
VLCC + BWTS7	0.178	0.175	**-2%**

Implying that our calculations by Microsoft Excel is validated by the results obtained by Expert Choice with regards to the most feasible BWTS alternative for the VLCC. Therefore, we can accept the reliability of the results derived by Expert Choice before proceeding with the sensitivity analysis in the next sections.

7.1.1 Sensitivity analysis of the global criteria

Table 7-2 presents four scenarios of the sensitivity analysis to the global criteria. The column "changes to" indicates that the ranking of the alternatives are changed. The column "Percentage of changes" shows which criteria are important. The most important criteria were shown with an asterisk; therefore their relevant pairwise comparisons should be carefully checked. The columns "Altered Cost or Safety or Regulation or Ship-compatibility weight (%) after sensitivity changes" indicates the altered weights of the other criteria for each individual scenario and each row in red must sum to 100%.

Table 7-2: Four scenarios of the sensitivity analysis to the global criteria

Scenario no.	Global criteria	Current weight (%)	Changes to	Percent of changes	Altered Cost weight (%) after sensitivity changes	Altered Safety weight (%) after sensitivity changes	Altered Regulation weight (%) after sensitivity changes	Altered ship-compatibility weight (%) after sensitivity changes
1	**Cost**	4.1	72.9	1678	72.9	8.1	14.8	4.2
2	**Safety**	28.5	48.5	70.2	3.0	48.5	37.8	10.7
3	**Regulation**	52.5	97.3	85.3	0.3	1.6	97.3	0.8
4	**Ship-compatibility**	14.9	5.0	-66.4*	4.5	31.8	58.9	5.0

Based on the sensitivity analysis shown in Table 7-2, ship compatibility (66.4%) appeared to be the most sensitive criterion amongst them. The negative percentage means a decreasing percentage of the current weight. However, this percentage means there is a little possibility that any changes to the priorities made to this particular criterion by the decision maker would alter the selected alternative for this VLCC as shown on the sensitivity graph in Figure 7-1. In order to examine the sensitivity of the ship-compatibility criterion, more discussions and analysis are performed under the robustness tests and case study two in the next sections in this chapter.

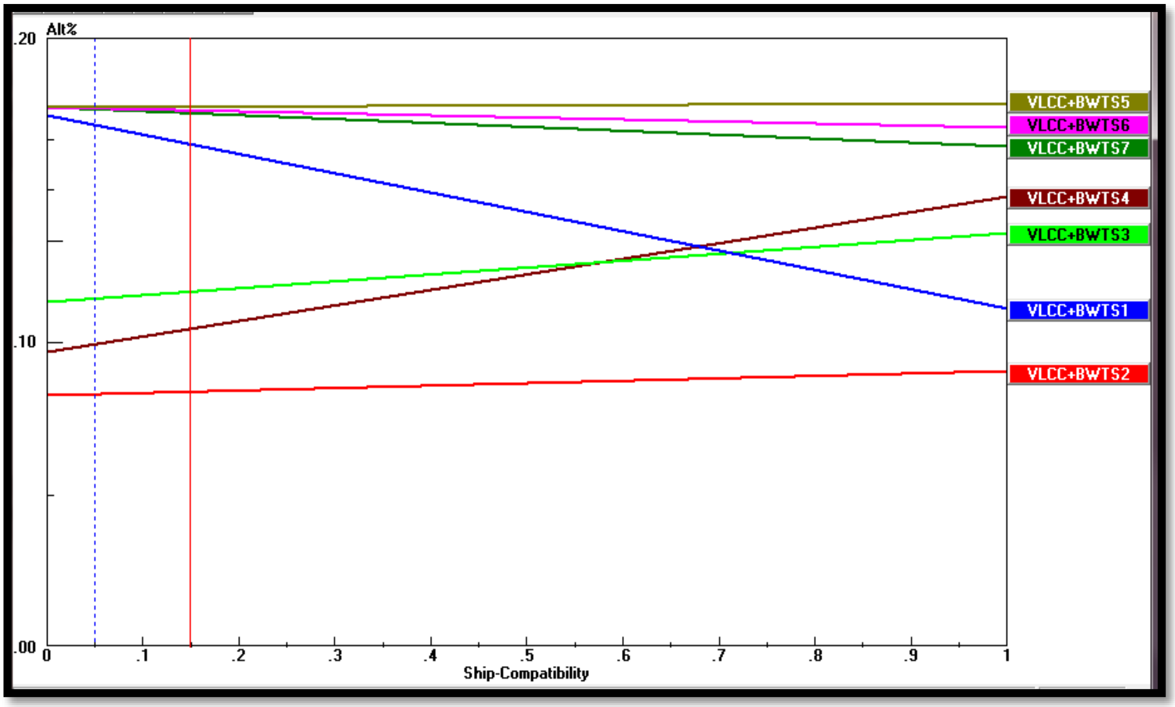

Figure 7- 1: Sensitivity analysis scenario on changes of the weight of the ship compatibility criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the ship compatibility criterion.

On the other hand, the criterion with a large percent of changes i.e. cost, safety and regulation implies a little possibility to change the selected alternative for any changes to these criteria for this VLCC as shown on the sensitivity graphs in Figure 7-2 to Figure 7-4. It is interesting to note, that the sensitivity of each criterion can be detected by checking the horizontal distance between the vertical lines i.e. red line which represent the current weight of the decision maker and the vertical dashed blue line which represent "change to" in each individual sensitivity graph.

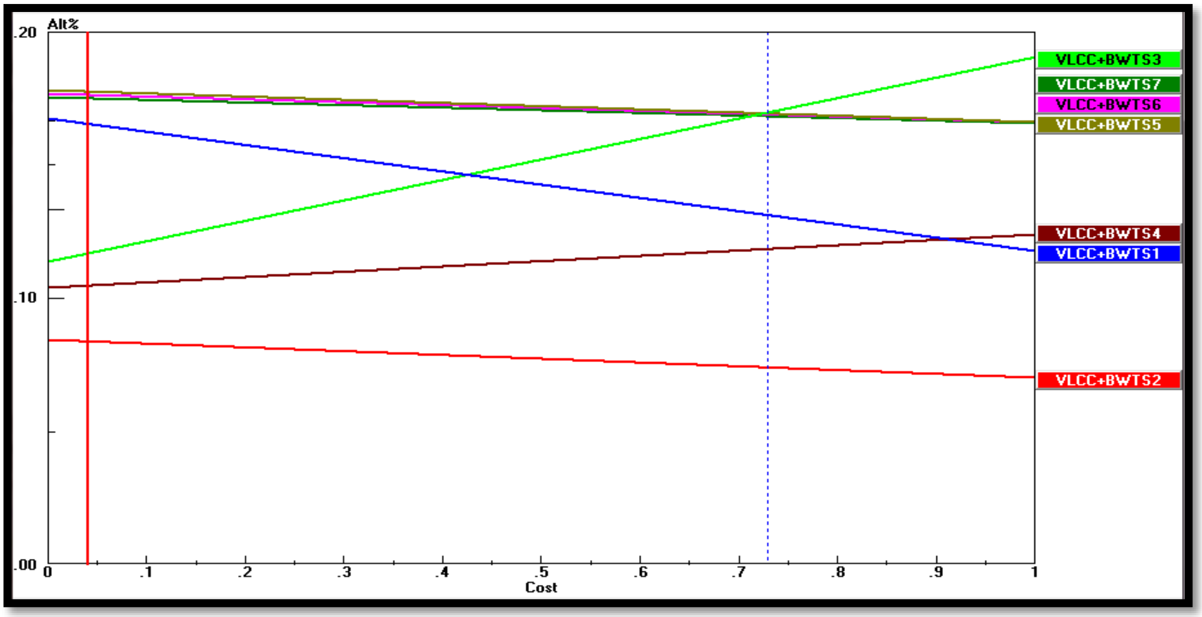

Figure 7- 2: Sensitivity analysis scenario on changes of the weight of the cost criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the cost criterion.

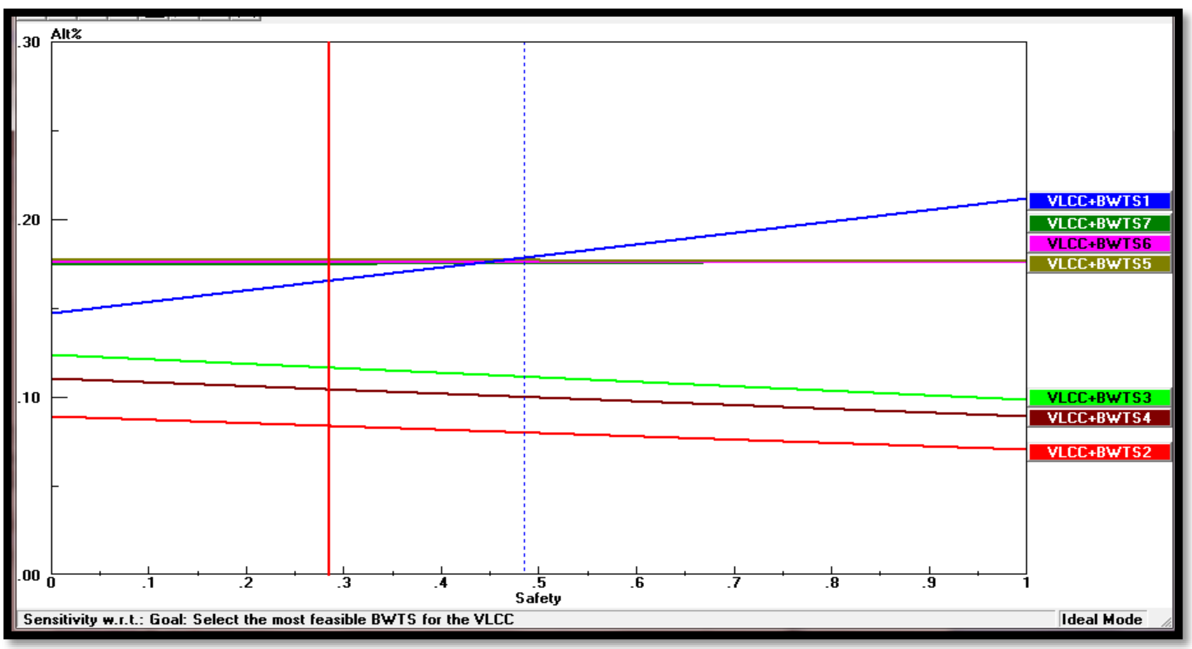

Figure 7- 3: Sensitivity analysis scenario on changes of the weight of the safety criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the safety criterion.

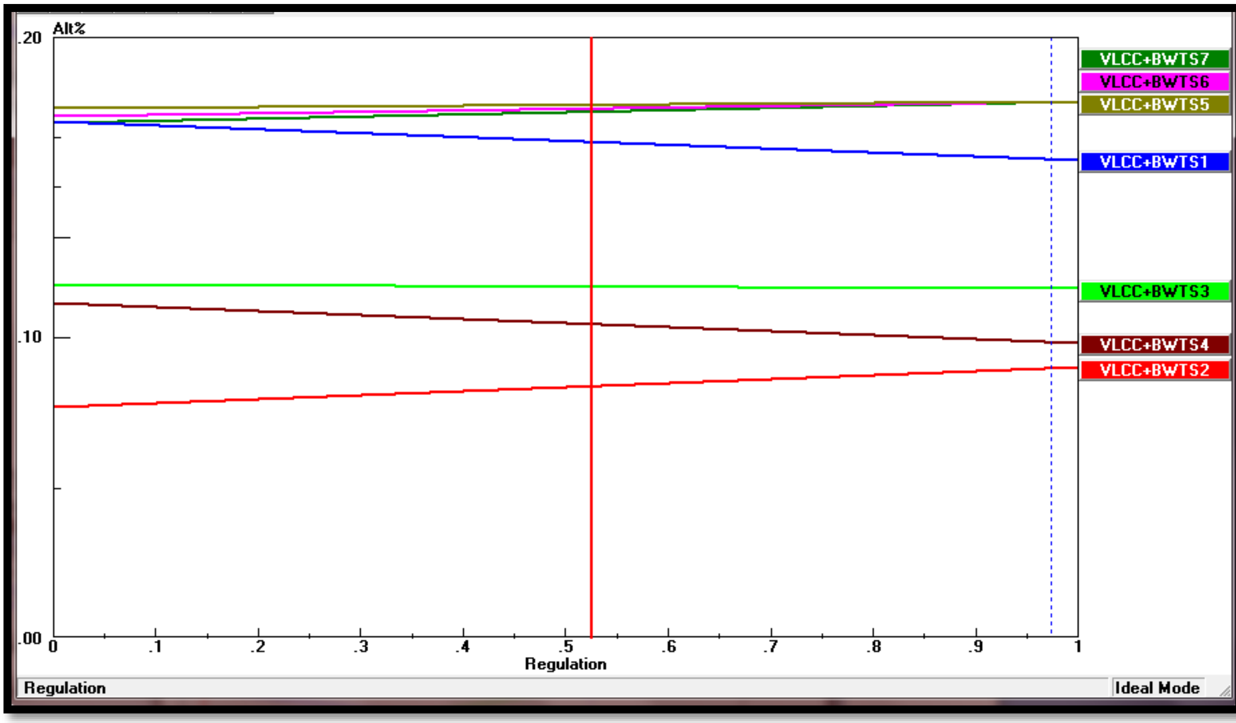

Figure 7- 4: Sensitivity analysis scenario on changes of the weight of the regulation criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the regulation criterion.

7.1.2 Sensitivity analysis of sub-criteria

In this section the sensitivity analysis of the sub-criteria is analysed in the same way as we did with the global criteria in section 7.1.1.

- **Sensitivity analysis of cost sub-criteria**

Table 7-3 presents three scenarios of the sensitivity analysis to the cost sub-criteria. The column "changes to" indicates that the ranking of the alternatives are changed. The column "Percentage of changes" shows which criteria are important. The most important criteria were shown with an asterisk; therefore their relevant pairwise comparisons should be carefully checked. The columns "Altered C1 or C2 or C3 weight (%) after sensitivity changes" indicates the altered weights of the other criteria for each individual scenario and each row in red must sum to 100%.

Table 7-3: Three scenarios of sensitivity analysis to the cost sub-criteria

Scenario no.	Cost Sub-criteria	Current weight (%)	Changes to	Percent of changes	Altered C1 Weight (%) after sensitivity changes	Altered C2 Weight (%) after sensitivity changes	Altered C3 Weight (%) after sensitivity changes
1	**Minimum capital cost (C1)**	33.3	23.9	-28*	23.9	38.1	38.1
2	**Minimum operating cost (C2)**	33.3	17.6	-47	41.2	17.6	41.2
3	**Minimum maintenance cost (C3)**	33.3	44.5	44.5	27.7	27.7	44.5

It is important to note that, this sensitivity analysis is performed with respect to the cost criterion and not the goal of the model. Based on the sensitivity analysis shown in Table 7-3, the minimum capital cost (C1) (28%) criterion appeared to be the most sensitive criterion amongst them. The negative sign means a decreasing percentage of the current weight. However, this percentage means that there is a little possibility that any changes to capital cost would alter the selected alternative for this VLCC as shown in sensitivity Table 7-2 and Figure 7-2.

The sensitivity graphs for the cost sub-criteria are presented on the graphs from Figure 7-5 to Figure 7-7.

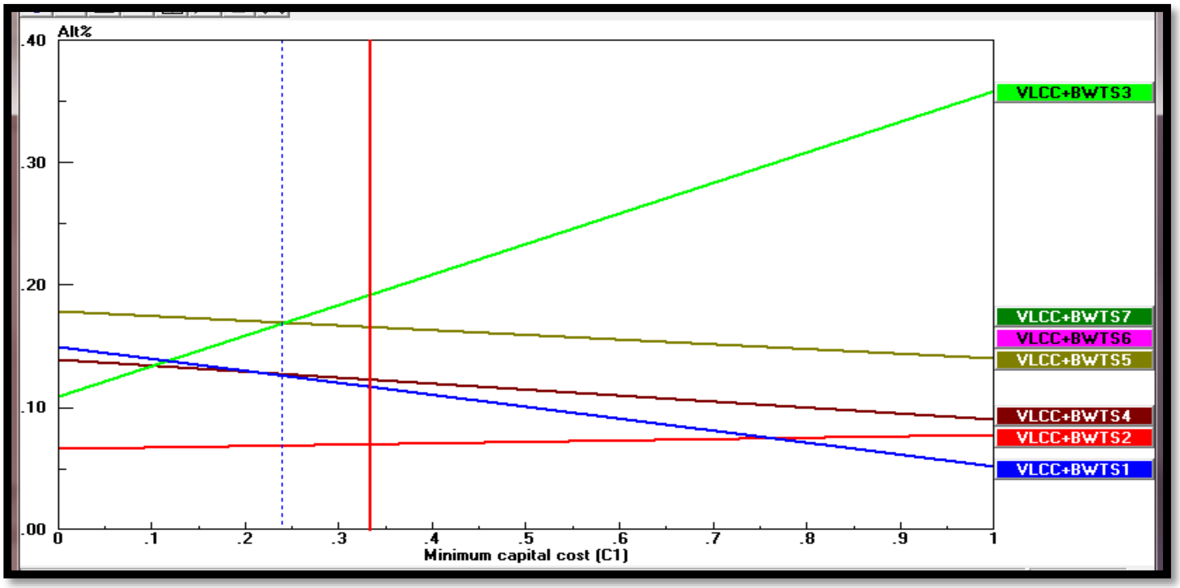

Figure 7- 5: Sensitivity analysis scenario on changes of the weight of the minimum capital cost (C1) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the minimum capital cost (C1) criterion.

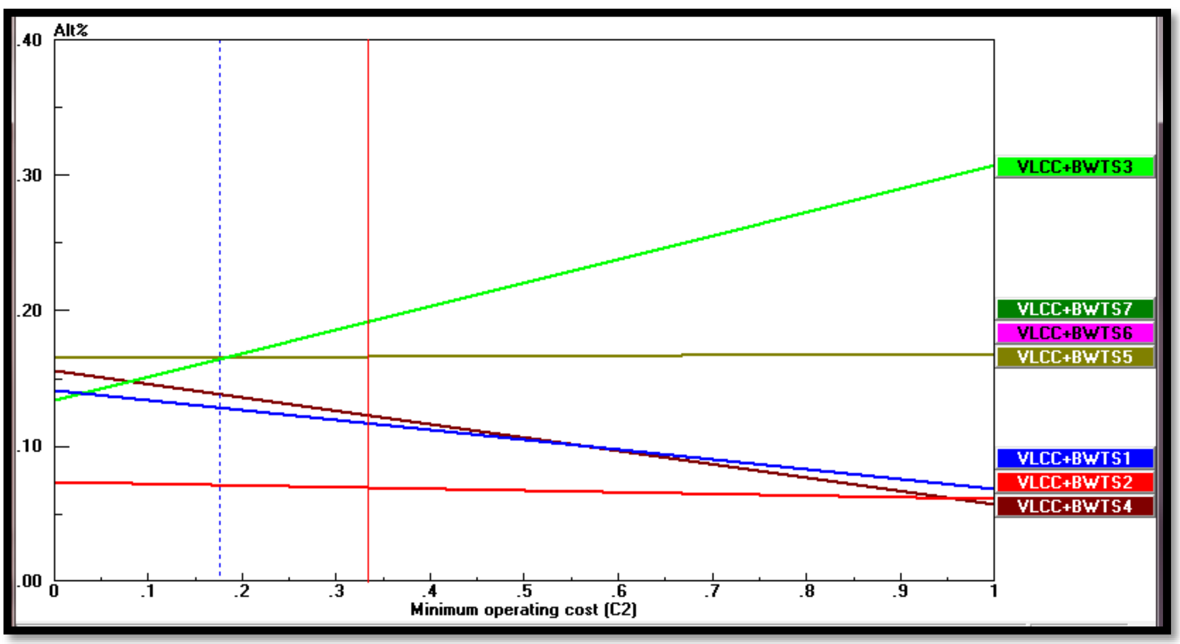

Figure 7- 6: Sensitivity analysis scenario on changes of the weight of the minimum operating cost (C2) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the minimum operating cost (C2) criterion.

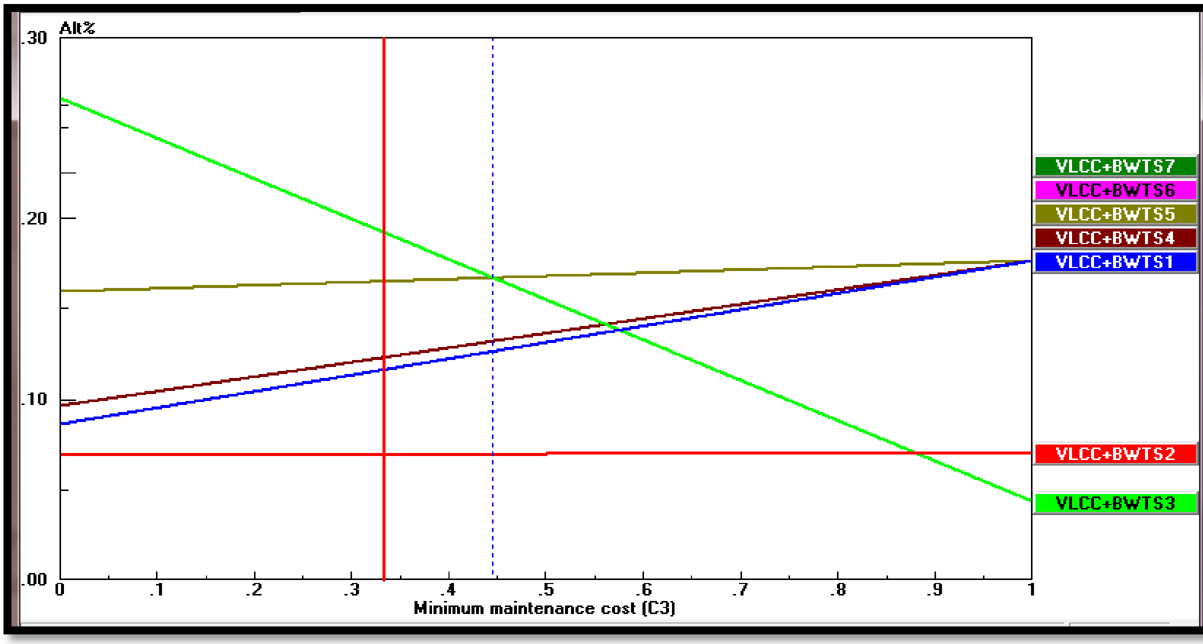

Figure 7- 7: Sensitivity analysis scenario on changes of the weight of the minimum maintenance cost (C3) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the minimum maintenance cost (C3) criterion.

It is important to remember that, according to the sensitivity analysis of the cost as a global criterion Table 7-2, changes to the sub-criteria will not alter the selected alternative for this VLCC. However, the derived conclusion by the sensitivity analysis Table 7-2 can be examined by considering the highest capital cost instead of the median average, and also by changing the discount rate from 6% to 8% and 12% with the assumption of constant operating cost for lifespan of the next 20 years.

In Table 7-4, the highest capital cost was extracted from Table 5-11 along with the calculated PV value for 8% and 12% discount rates. The operating cost of each BWTS alternative is assumed to be constant. As shown in Table 7-4, considering the highest capital cost, the UV treatment is shown as the least cost effective type treatment among other alternatives. These values are normalised and the vector of priorities is obtained as shown in Table 7-5.

Table 7- 4: The identified average highest capital based on the collected data from Table 5-11 for each BWTS disinfection alternative and the calculated PV value for 8$ and 12% discount rate.

Disinfection method	Highest capital cost ($)	Highest PV ($) at 8% discount rate	Highest PV ($) at 12% discount rate
Ultraviolet irradiation (UV)	4,000,000.00	4,647,997.00	4,492,983.00
Chlorine	1,000,000.00	2,885,084.00	2,434,133.00
Chlorine dioxide	660,000.00	1,013,453.00	928,899.00
Ozone treatment	1,600,000.00	3,367,266.00	2,944,499.00
Electro-chlorination	750,000.00	1,633,633.00	1,422,249.00
De-Oxygenation	800,000.00	2,390,539.00	2,010,049.00

Table 7- 5: The obtained vector of priority of the minimum capital cost criterion, based on the highest capital cost values in Table 7-4

BWTS disinfection method	denoted	Vector of priority of the minimum capital cost at 8% discount rate	Vector of priority of the minimum capital cost at 12% discount rate
De-Oxygenation	BWTS1	0.155	0.166
Ozone treatment	BWTS2	0.110	0.114
Chlorine dioxide treatment	BWTS3	0.366	0.360
Chlorine treatment	BWTS4	0.129	0.137
Ultraviolet irradiation treatment (UV)	BWTS5	0.080	0.074
Ultraviolet irradiation treatment (UV)	BWTS6	0.080	0.074
Ultraviolet irradiation treatment (UV)	BWTS7	0.080	0.074

It is important to note that, the increase of the discount rate from 8% to 12% have decreased PV value of the BWTS alternatives. Although these differences have been indicated in Table 7-5 by both vector of priorities as scores assigned for each BWTS alternative, they have not significantly influenced the ranks or the order between the given BWTS alternatives. Therefore, it is adequate to consider the analysis of only one vector of priority in Table 7-5 next.

As shown in Table 7-5, BWTS3 was selected as the most cost effective alternative amongst the given BWTS alternatives under both discount rates 8% and 12%. BWTS3 (0.366) alternative has scored or performed better under the minimum capital cost criterion (C1). On the other hand, BWTS5-7 have been indicated as the least preferred alternatives amongst the given BWTS alternatives to satisfy the minimum capital cost criterion as expected and shown on the graph in Figure 7-8.

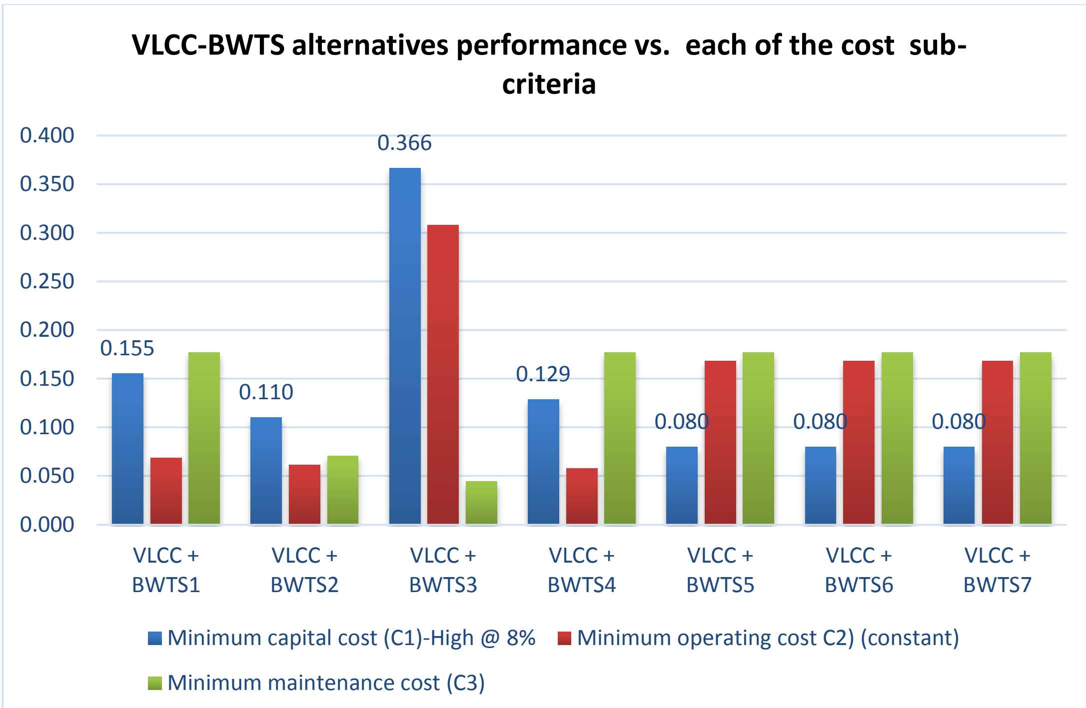

Figure 7- 8: VLCC-BWTS alternatives performance vs. each of the cost sub-criteria, using the highest capital cost at 8% discount rate.

By combining all these facts in Figure 7-8, the obtained result is shown in Figure 7-9. In Figure 7-9, the results are expected, because VLCC+BWTS3 (0.240) performed or scored better than all other alternatives under both the minimum capital cost criterion (C1) and the operating cost criterion (C2). However, VLCC+BWTS3 did not perform well under the minimum maintenance cost (C3). On the other hand, VLCC+BWTS5-7 (0.142) alternatives have been shown equally as the 2nd preferred alternatives to satisfy the cost as a global criterion. This is because VLCC+BWTS5-7 (0.177) alternatives have equally scored or performed better than other alternatives under the minimum maintenance cost

(C3) criterion. In addition, VLCC+BWTS5-7 alternatives have also equally scored the 2nd preferred alternatives under the minimum capital cost (C2) criterion.

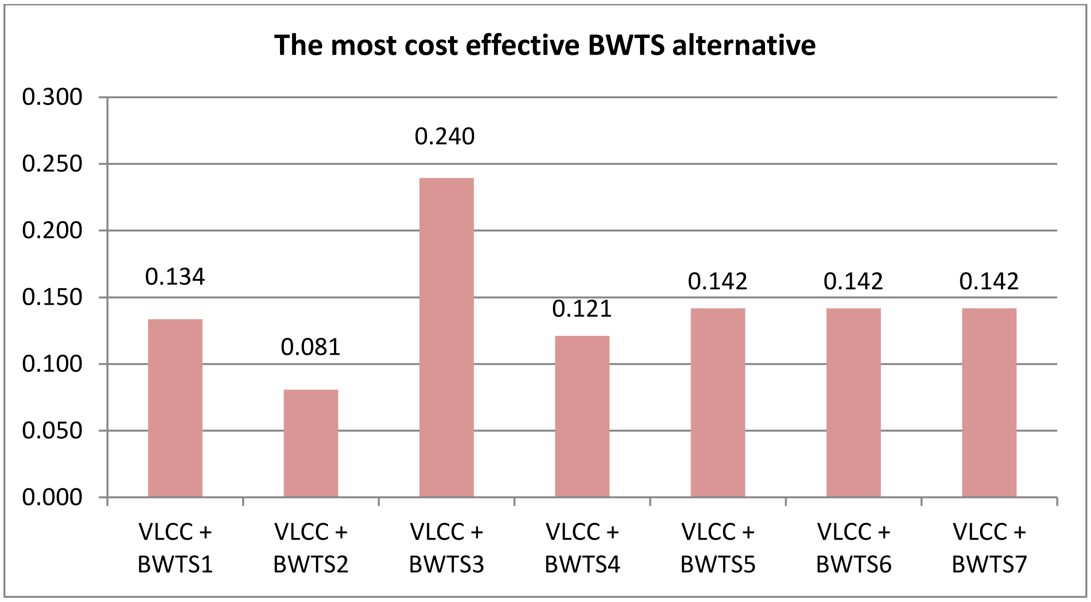

Figure 7- 9: The alternatives order for the cost criterion after considering the highest capital cost

Re-running the model, the outcome of it with the consideration of the highest capital cost is shown in Figure 7-10 and Figure 7-11. In Figure 7-10, the performance of the seven BWTS alternatives versus the global criteria can be summarised below:

- VLCC+BWTS3 (0.240) alternative has been indicated at the most preferred alternative to the cost criterion as expected.
- VLCC+BWTS1 alternative (0.225) is the most preferred alternative to the safety criterion as expected.
- VLCC+BWTS5 alternative (0.189) is the most preferred alternative to the ship-compatibility criterion expected.
- VLCC+BWTS5-7 alternative (0.182) is the most preferred alternative to the Regulation criterion as expected.

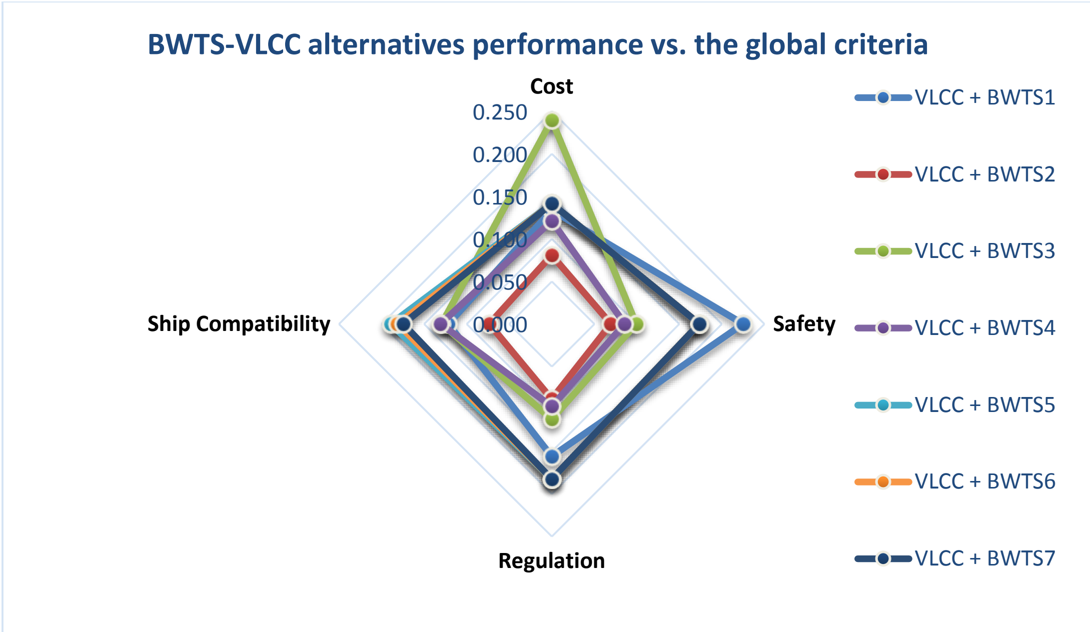

Figure 7- 10: The VLCC+BWTS alternatives performance after considering the highest capital cost values at 8% discount rate.

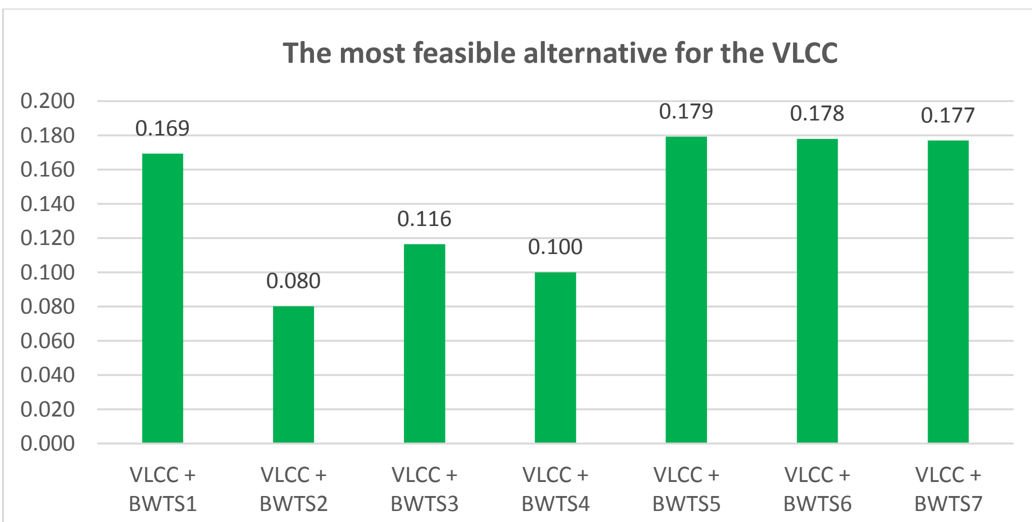

Figure 7- 11: The most feasible VLCC-BWTS alternative selected by the model after considering the highest capital cost value at 8% discount rate

Clearly from Figure 7-11, VLCC+BWTS5 alternative (0.179) has been selected by the model as the most feasible BWTS alternative for the given VLCC as indicated by the sensitivity analysis Table 7-2 as expected. This is because, VLCC+BWTS5 alternative has scored better amongst the given alternatives under the identified criteria by the model as shown in Figure 7-10. Therefore, the derived results by changing the cost i.e. by considering the highest capital cost of the alternatives, have validated the applicability of the model to perform according to the conclusions derived from the sensitivity analysis in Table 7-2 as expected.

- **Sensitivity analysis of safety sub-criteria**

Table 7-6 presents three scenarios of the sensitivity analysis to the safety sub-criteria. The column “changes to” indicates that the ranking of the alternatives are changed. The column “Percentage of changes” shows which criteria are important. The most important criteria were shown with an asterisk; therefore their relevant pairwise comparisons should be carefully checked. The columns “Altered S1 or S2 or S3 weight (%) after sensitivity changes” indicates the altered weights of the other criteria for each individual scenario and each row in red must sum to 100%.

Table 7-6: Three scenarios of the sensitivity analysis for the safety sub-criteria

Scenario no.	Safety Sub-criteria	Current weight (%)	Changes to	Percent of changes	Altered S1 Weight (%) after sensitivity changes	Altered S2 Weight (%) after sensitivity changes	Altered S3 Weight (%) after sensitivity changes
1	Maximum environmental safety (S1)	33.3	99.2	198	99.2	0.4	0.4
2	Maximum ship safety (S2)	33.3	13.8	-59*	43.1	13.8	43.1
3	Maximum crew safety (S3)	33.3	99.2	198	0.4	0.4	99.2

Based on the sensitivity analysis shown in Table 7-4, Maximum ship safety (59%) appeared to be the most sensitive criterion amongst them. The negative sign means decreasing percentage of the current weight.

As indicated in Table 7-2, changes to the latter criterion can be criterial; however, this change will have very little possibilities to alter the selected alternative for this VLCC. The sensitivity graphs of the safety sub criteria are presented in Figure 7-12 to Figure 7-14.

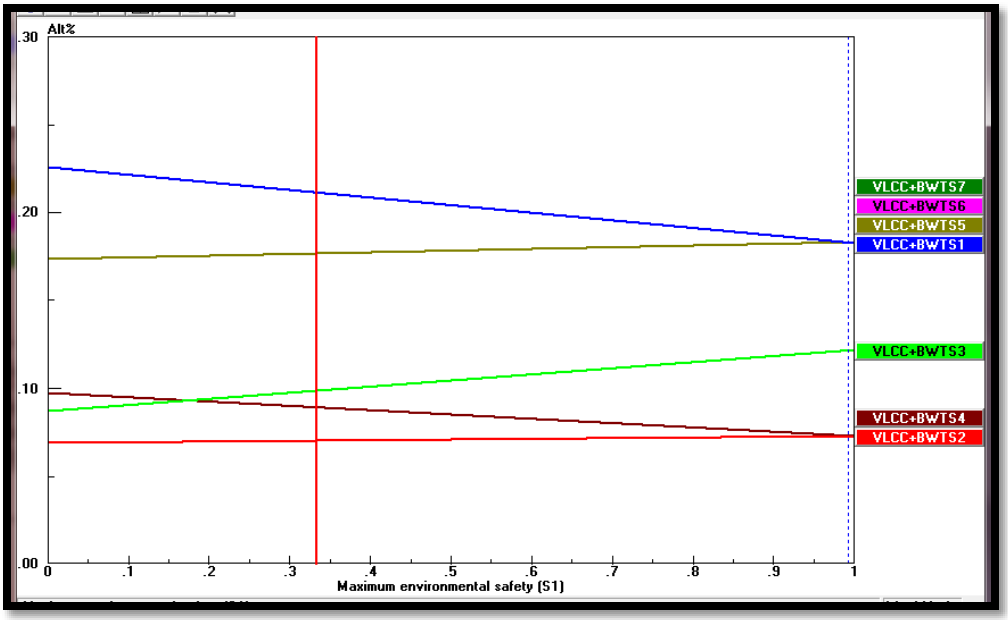

Figure 7- 12: Sensitivity analysis scenario on changes of the weight of the maximum environmental safety (S1) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the maximum environmental safety (S1) criterion.

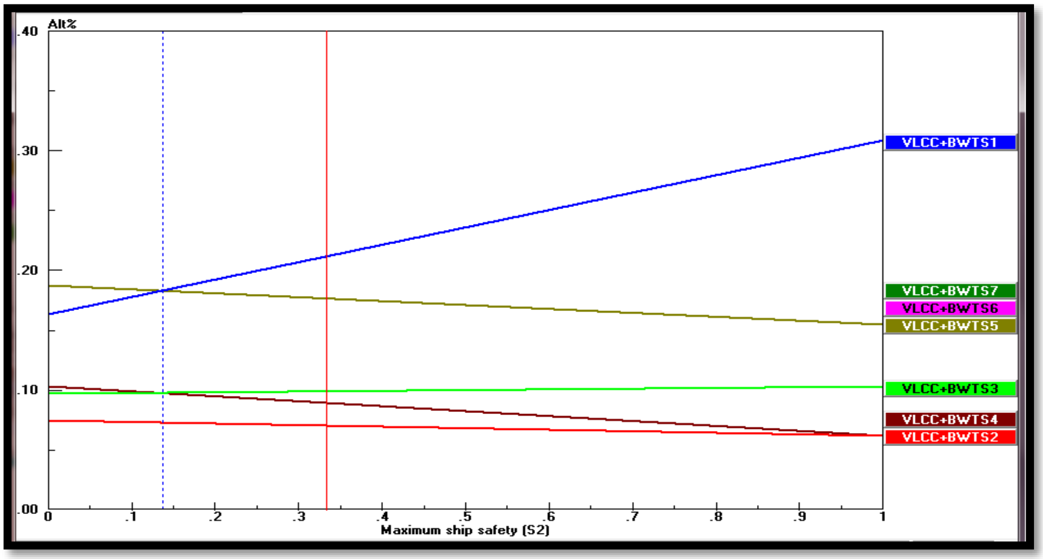

Figure 7- 13: Sensitivity analysis scenario on changes of the weight of the maximum ship safety (S2) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the maximum ship safety (S2) criterion.

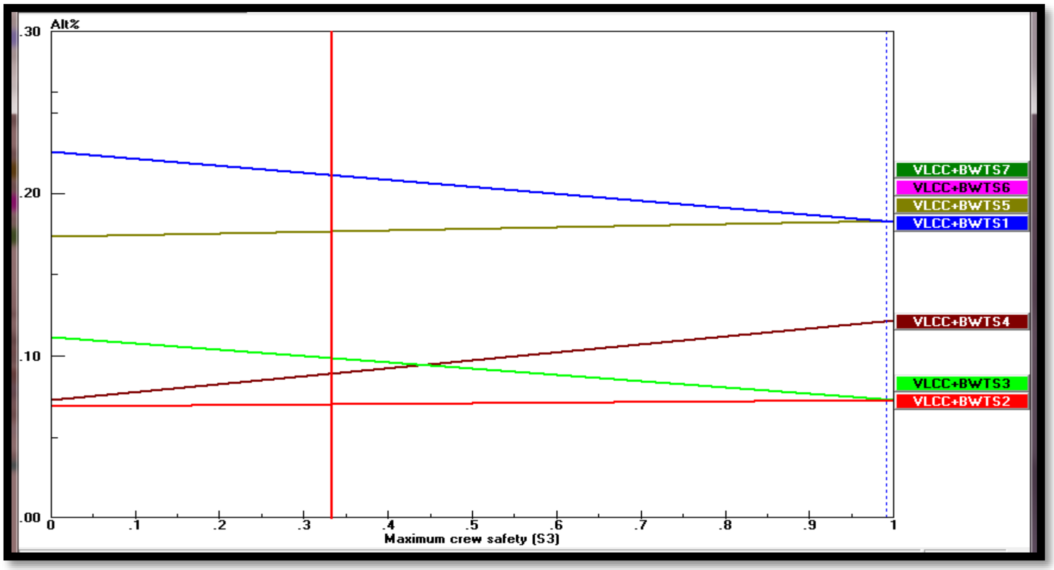

Figure 7- 14: Sensitivity analysis scenario on changes of the weight of the maximum crew safety (S3) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the maximum crew safety (S3) criterion.

- **Sensitivity analysis of regulation sub-criteria**

Table 7-7 presents four scenarios of the sensitivity analysis to the regulation sub-criteria. The column "changes to" indicates that the ranking of the alternatives are changed. The column "Percentage of changes" shows which criteria are important. The most important criteria were shown with an asterisk; therefore their relevant pairwise comparisons should be carefully checked. The columns "Altered B1 or B2 or B3 OR B4 weight (%) after sensitivity changes" indicates the altered weights of the other criteria for each individual scenario and each row in red must sum to 100%.

Table 7-7: Four scenarios of sensitivity analysis for the regulation sub-criteria

Scenario no.	Regulation sub-criteria	Current weight (%)	Changes to	Percent of changes	Altered B1 weight (%) after sensitivity changes	Altered B2 weight (%) after sensitivity changes	Altered B3 weight (%)after sensitivity changes	Altered B4 weight (%)after sensitivity changes
1	Minimum influence on changes to seawater temperature (B1)	25.0	10.9	-56	10.9	29.7	29.7	29.7
2	Minimum influence on changes to seawater salinity (B2)	25.0	97.6	290	0.8	97.6	0.8	0.8
3	Minimum influence on changes to seawater organic concentration (B3)	25.0	13.3	-47	28.9	28.9	13.3	28.9
4	Minimum influence on changes to seawater clarity (B4)	25.0	33.1	32*	22.3	22.3	22.3	33.1

Based on the sensitivity analysis shown in Table 7-7, the minimum influence on changes to seawater clarity (B4) criterion (32%) appeared to be the most sensitive criterion amongst them. The negative sign means a decreasing percentage of the current weight.

As indicated by the sensitivity analysis in Table 7-2, changes to the regulation criterion, will have very little possibilities to alter the selected alternative for this VLCC. This is because regulation criterion as shown in Table 7-2 is not a sensitive criterion to alter the selected alternative for this VLCC.

The sensitivity graphs of the regulation sub-criteria are presented in Figure 7-15 to Figure 7-18.

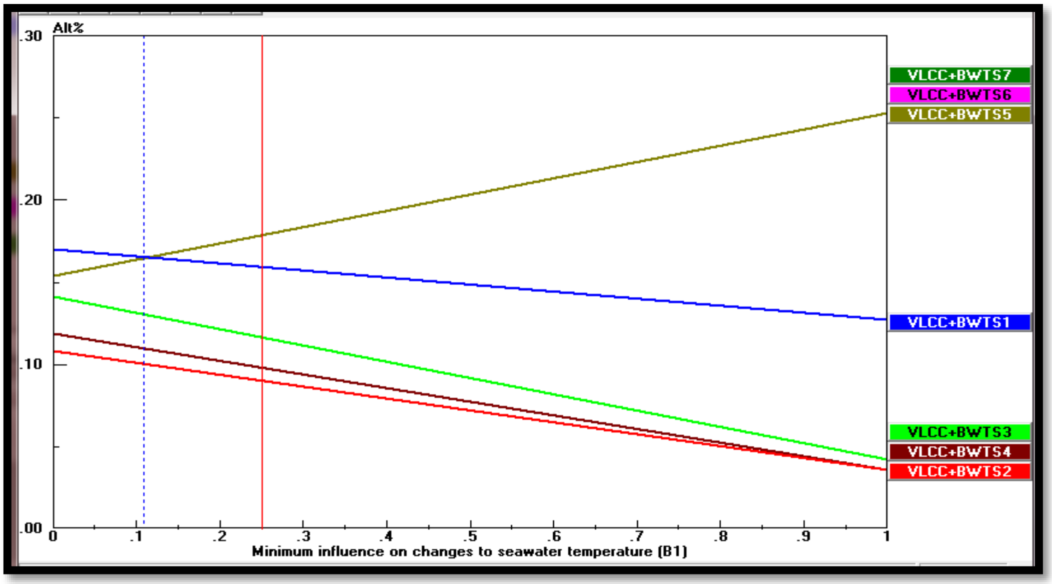

Figure 7- 15: Sensitivity analysis scenario on changes of the weight of the minimum influence on changes to seawater temperature (B1) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the B1 criterion.

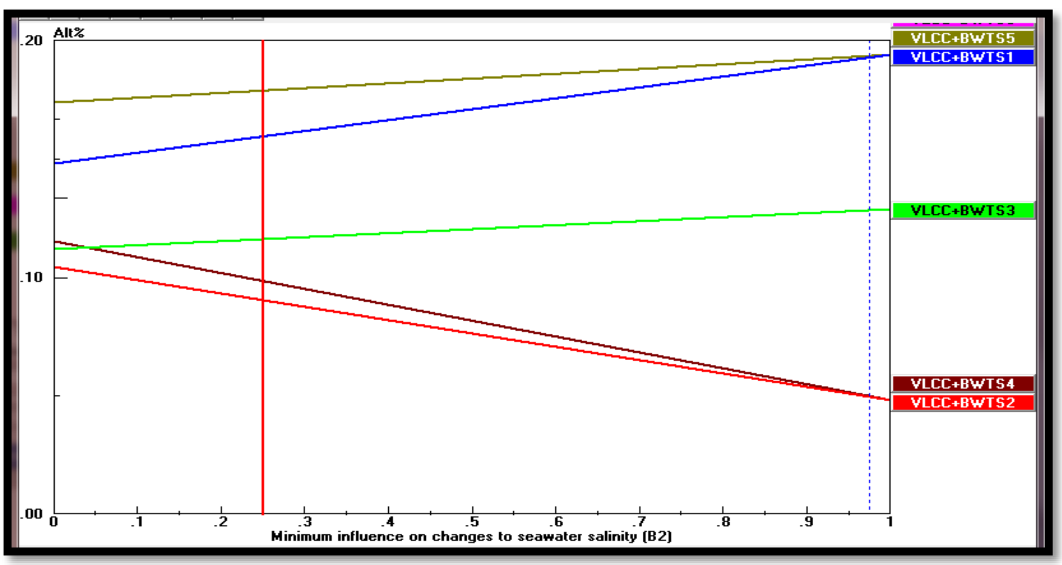

Figure 7- 16: Sensitivity analysis scenario on changes of the weight of the minimum influence on changes to seawater salinity (B2) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the B2 criterion.

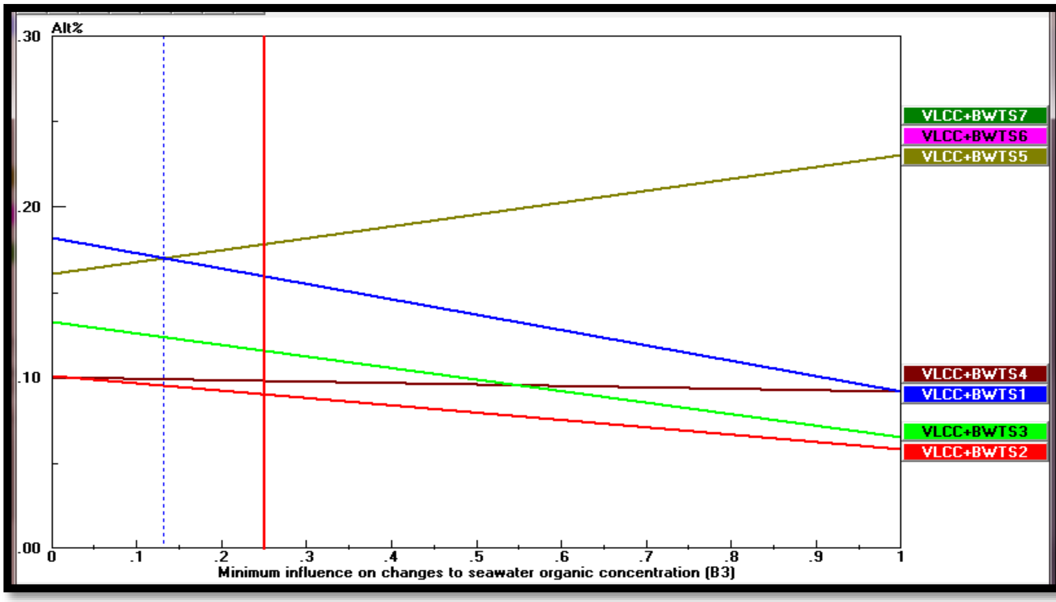

Figure 7- 17: Sensitivity analysis scenario on changes of the weight of the minimum influence on changes to seawater organic concentration (B3) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the B3 criterion.

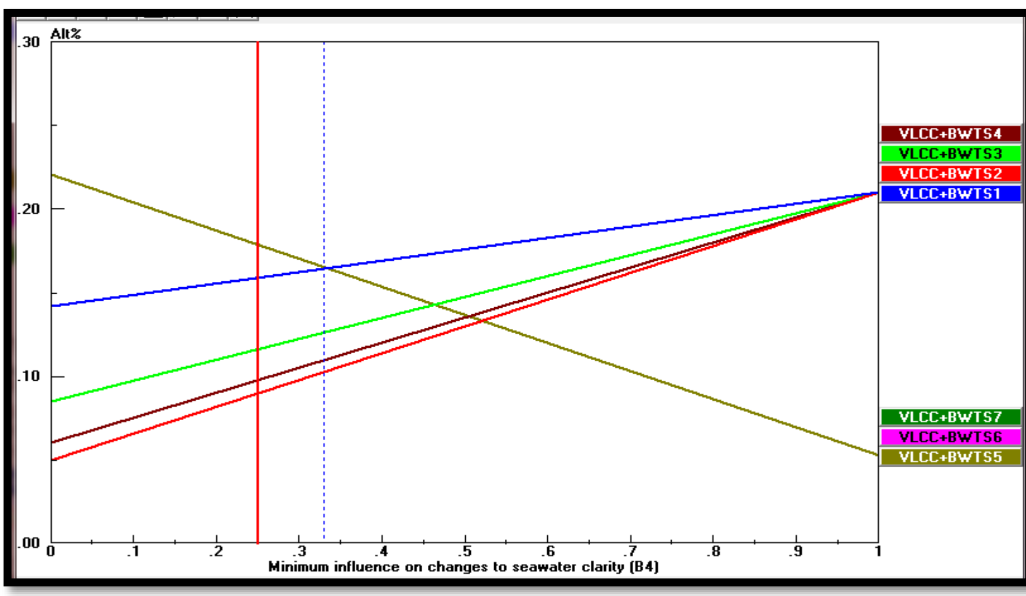

Figure 7- 18: Sensitivity analysis scenario on changes of the weight of the minimum influence on changes to seawater clarity (B4) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the B4 criterion.

- **Sensitivity analysis of ship compatibility sub-criteria**

Table 7-8 presents six scenarios of the sensitivity analysis to the ship-compatibility sub criteria. The column "changes to" indicates that the ranking of the alternatives are changed. The column "Percentage of changes" shows which criteria are important. The most important criteria were shown with an asterisk; therefore their relevant pairwise comparisons should be carefully checked. The columns "Altered SH1 or SH2 or SH3 or SH4 or SH5 or SH6 weight (%) after sensitivity changes" indicates the altered weights of the other criteria for each individual scenario and each row in red must sum to 100%.

Table 7-8: Six scenarios of the sensitivity analysis for ship-compatibility sub-criteria

Scenario no.	Regulation sub-criteria	Current weight (%)	Changes to	Percent of changes	Altered SH1 weight (%) after sensitivity changes	Altered SH2 weight (%) after sensitivity changes	Altered SH3 weight (%) after sensitivity changes	Altered SH4 weight (%) after sensitivity changes	Altered SH5 weight (%) after sensitivity changes	Altered SH6 weight (%) after sensitivity changes
1	Satisfying limited space (SH1)	11.1	73.3	560	73.3	4.7	4.7	3.8	8.6	4.9
2	Satisfying process time (SH2)	15.8	97.9	520	0.6	97.9	0.3	0.3	0.6	0.3
3	Maximum ability to treat ship ballast water capacity (SH3)	15.8	98.9	526	0.1	0.2	98.9	0.2	0.4	0.2
4	Minimum interruption at ship emergency (SH4)	12.8	97.3	660	0.3	0.5	0.5	97.3	0.9	0.5
5	Maximum ease of operation (SH5)	28.4	98.2	246	0.3	0.4	0.4	0.3	98.2	0.4
6	Minimum ship operating cost (SH6)	16.3	48.4	197*	6.8	9.7	9.7	7.9	17.5	48.4

Based on the sensitivity analysis shown in Table 7-8, minimum ship operating cost (SH6) (197%) appeared to be the most sensitive criterion amongst them. Although ship compatibility was indicated earlier in Table 7-2 as the most criterial criterion, the large percent of changes shown in Table 7-8 implies a very little possibility to alter the selected alternative for this VLCC.

The sensitivity graphs for ship-compatibility sub criteria are presented from Figure 7-19 to Figure 7-25.

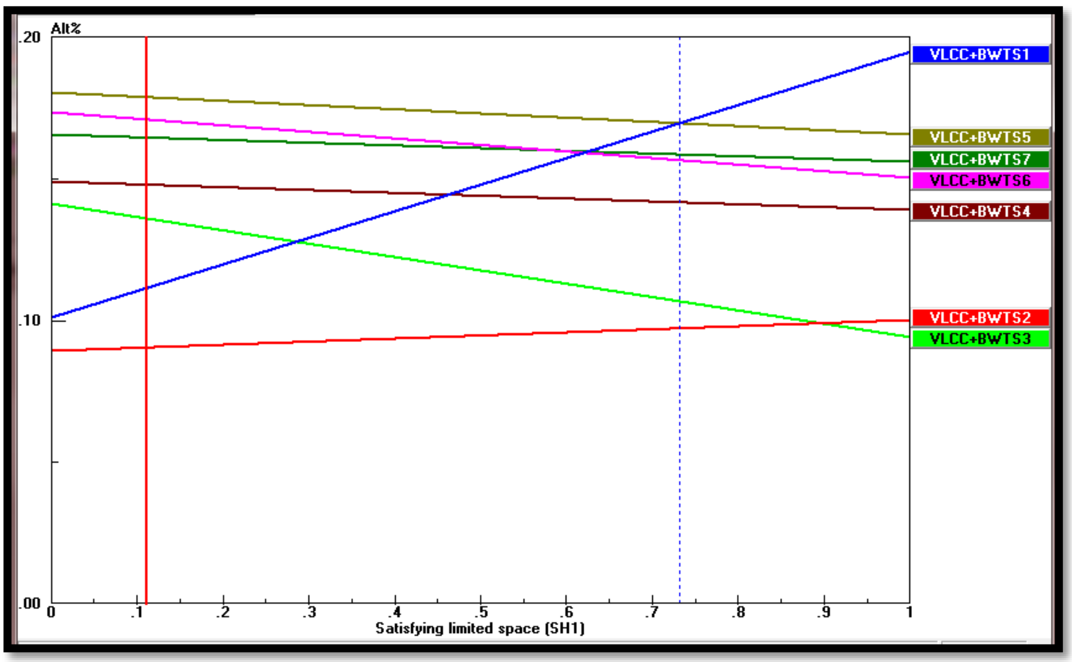

Figure 7- 19: Sensitivity analysis scenario on changes of the weight of satisfying limited space (SH1) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the SH1criterion.

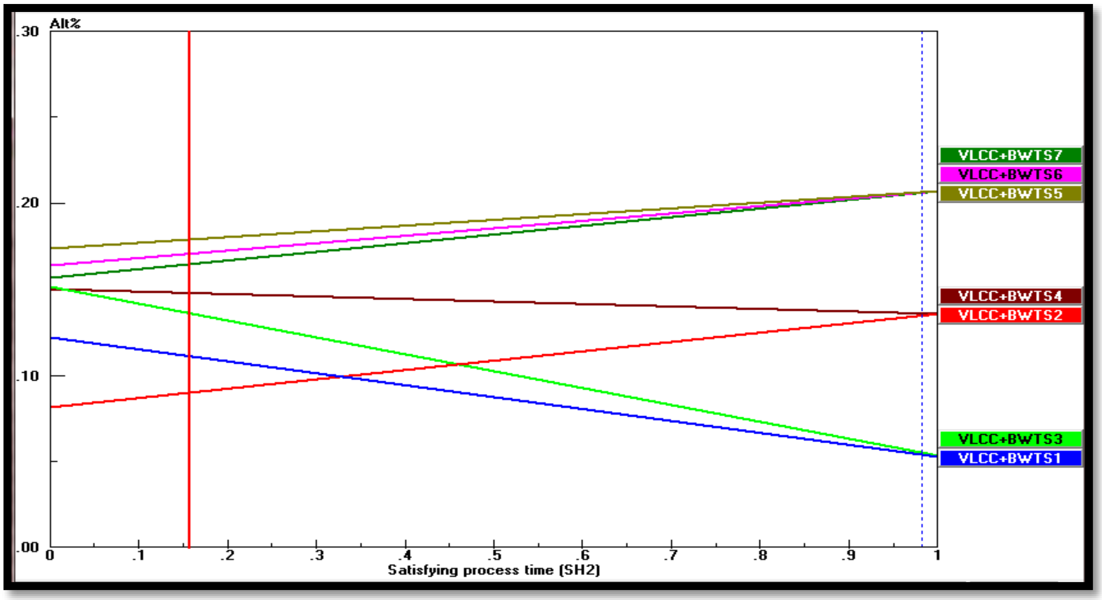

Figure 7- 20: Sensitivity analysis scenario on changes of the weight of satisfying process time (SH2) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the SH2 criterion.

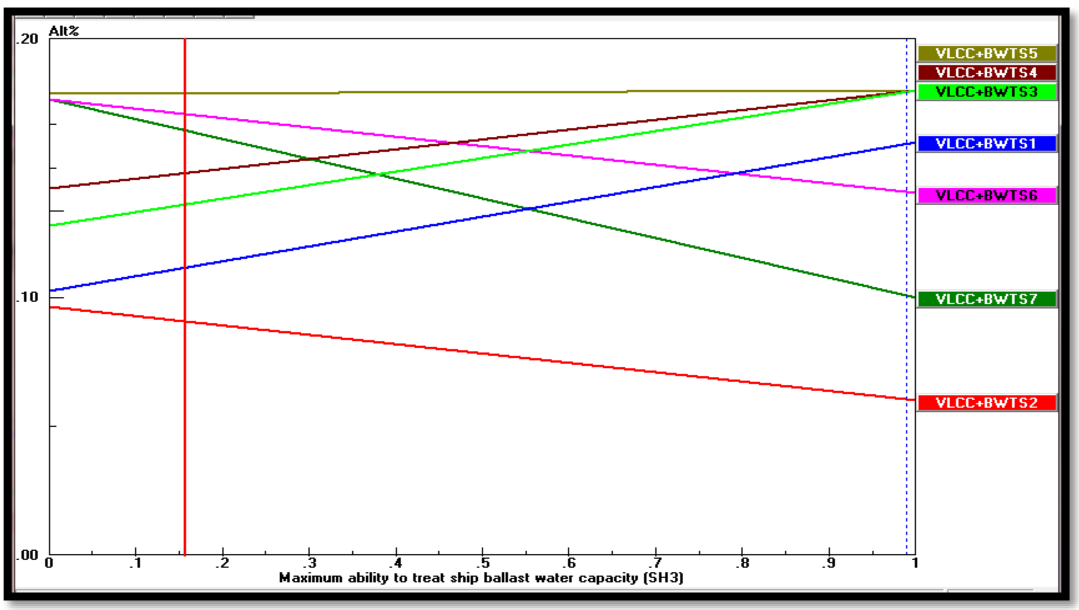

Figure 7- 21: Sensitivity analysis scenario on changes of the weight of the maximum ability to treat ship BW capacity (SH3) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the SH3 criterion.

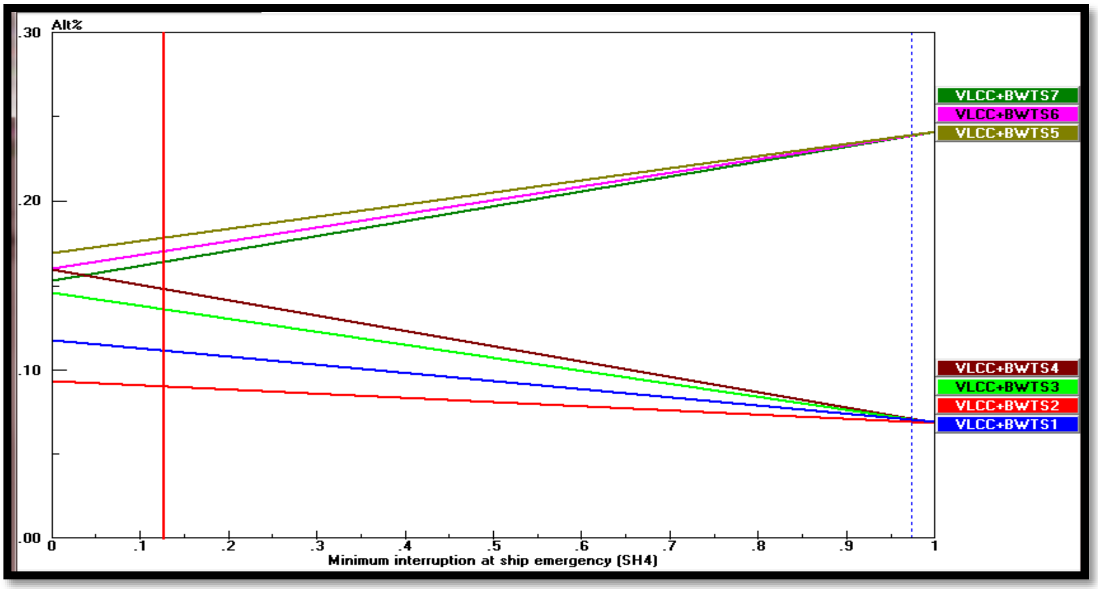

Figure 7- 22: Sensitivity analysis scenario on changes of the weight of the minimum interruption at ship emergency (SH4) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the SH4 criterion.

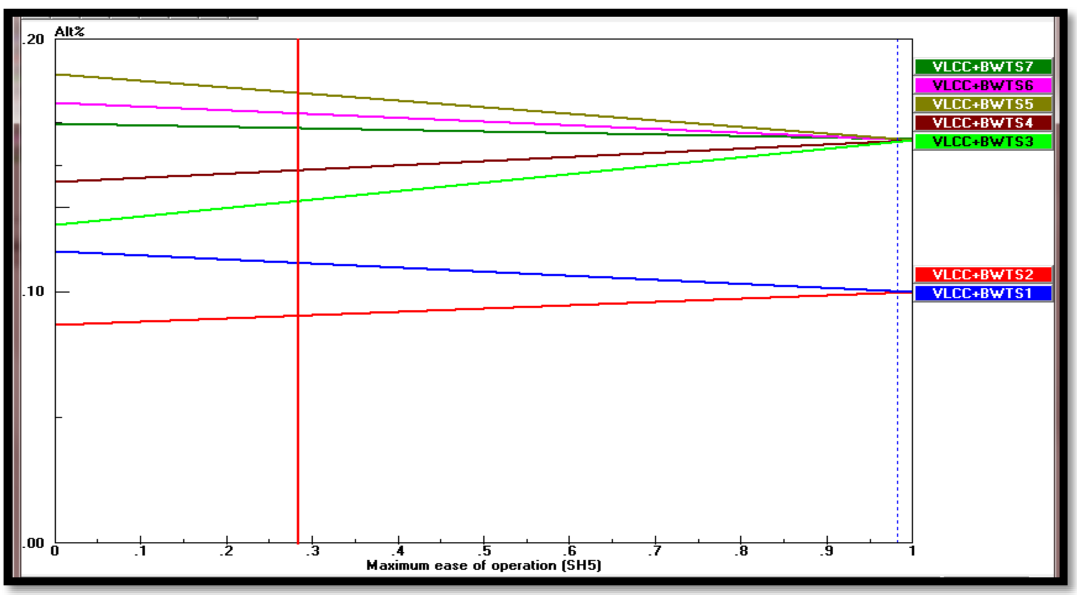

Figure 7- 23: Sensitivity analysis scenario on changes of the weight of the maximum ease of operation (SH5) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the SH5 criterion.

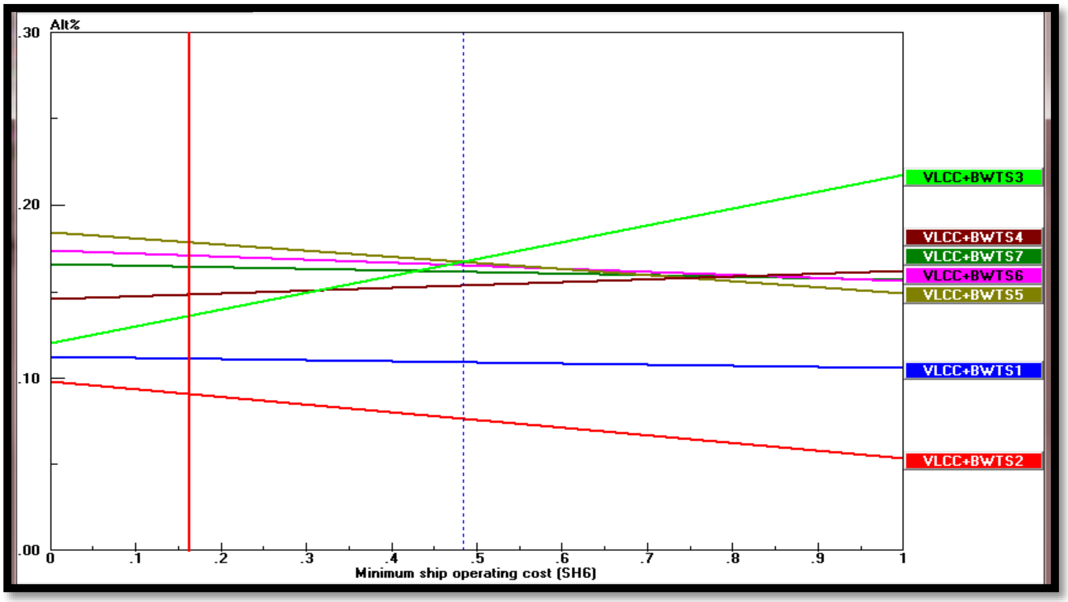

Figure 7- 24: Sensitivity analysis scenario on changes of the weight of the minimum ship operating cost (SH6) criterion against the change of the selected alternative; The vertical red line represents the current weight, The vertical blue dashed line represents "the changed to" weight; The x-Axis represents the priority vector, the y-Axis on the left hand side represents the decisions scores of each alternative, the different colours lines represent the performance of each BWTS alternative versus the change on the current weight of the SH6 criterion.

7.1.3 Robustness test

The results were based on the aggregated data and information from the three inputs to the model as discussed in chapter 5&6. The case study discussed in chapter-5&6 will be denoted as case study one of the model, hereafter, which has selected BWTS5 alternative (0.180) as the most feasible alternative of the VLCC.

The sensitivity analysis of the criteria was performed by changing the relative importance of criteria and sub-criteria in order to find out the critical criterion that requires careful consideration by the decision maker. The sensitivity analysis indicated in Table 7-2 that the outcome of the selected VLCC+BWTS5 alternative will remain the most feasible alternative amongst the given alternatives for this VLCC. On other words, any changes in the priorities of the cost and regulation can be considered critical, yet it was proven under the cost sub-criteria analysis that the cost alteration did not cause any change to the selected alternative for this VLCC as expected. On the other hand, the ship-compatibility criterion was identified in Table 7-2 as the most critical criterion; however, the large percentage of change implied a little possibility to alter the selected alternative for this VLCC.

Based on this information derived by the sensitivity analysis, two robustness tests were put forward a null test denoted (**H_0**) and an alternative test denoted (**H_1**) stating:

- **H_0:** with all other criteria remains the same for the VLCC. Changing the priorities of the ship compatibility criterion by changing any of its sub criteria (indicators) such as satisfying length voyage criterion through changing the ship's voyage length, the outcome of the model **will not alter** the selected alternative.
- **H_1:** with all other criteria remains the same for the VLCC. Changing the priorities of the ship compatibility criterion by changing any of its sub criteria (indicators) such as satisfying length voyage criterion through changing the ship's voyage length, the outcome of the model **will alter** the selected alternative.

In order to test the above two robustness tests, case study one has been slightly changed by changing the trade route and the voyage length of the VLCC in case study two.

Case study two is discussed next.

7.2 Case study two

In order to examine and test the conclusion derived from the sensitivity analysis of case study one, case study two will look at the changes to results obtained in case one by the same model for the same VLCC under different trade route as shown in Table 7-9.

Table 7-9: VLCC voyage information (case study two): VLCC voyage information: loading and unloading regions, cargo operation, voyage length, temperature differences and salinity approximations.

ports legs	cargo operation	Sailing distance (nautical miles)	days at sea	days in port	Region	Ave. low temp ˚C	Ave. high temp ˚C	approx. Salinity (g/kg)
South Africa to China	Loading	8699	24	6	Angola	15.5	27.6	35.5 - 36.5
	Discharging			6	Huizhou	15	22.4	34 - 34.5

The VLCC voyage information was simplified to cope with the model as presented in Table 7-9. In Table 7-9, the temperature differences between the regions were acquired from (weatherbase, 2014). The salinity approximations were acquired from (NASA, 2014).

In case study two, the VLCC unload cargo in Huizhou (China), fill in ballast water tanks in order to maintain the required safe operation under various weather conditions by adjusting the trim while maintaining the optimum speed of the ship before it reaches Angola port (South Africa) fully ballasted. In this leg, the VLCC got 24 days to reach back to Angola in order to load cargo. The approximated average high and low seawater temperature's difference between Angola and Huizhou (China) as geographic locations ports is 0.5˚C (i.e. 15.5˚C - 15˚C = 0.5˚C; average high seawater temperature difference between the two locations is 9.6˚C i.e. 27.6˚C - 22.4˚C = 5.2˚C).

In case study two the VLCC's loading location was changed and thus lengthened its voyage duration from 14 days i.e. in case study one into 24 days i.e. in case study two. This means that all the other criteria remained the same as in case study one; however, the priority of the ship compatibility criterion has been changed by altering the process time and voyage length criteria.

Synthesising the ship particulars, voyage information, BWTS alternatives alongside with the importance or preferences obtained from the decision maker, will enable finding the output of the model. The results or the outcome of case study two should enable to test the derived conclusion of the sensitivity analysis and the hypotheses.

The details of the derived results are discussed in the next sections.

7.2.1 Results derived from case study two

All the obtained results and calculations in case study one for the priority vectors of all the criteria were the same. The only difference in case study two is the length of the voyage for the VLCC by changing the loading region.

The priorities were calculated for the ship compatibility criterion based on the changes to the length of voyage and satisfying the process time criteria only as shown on the graph in Figure 7-25 with respect to the ship-compatibility criterion only.

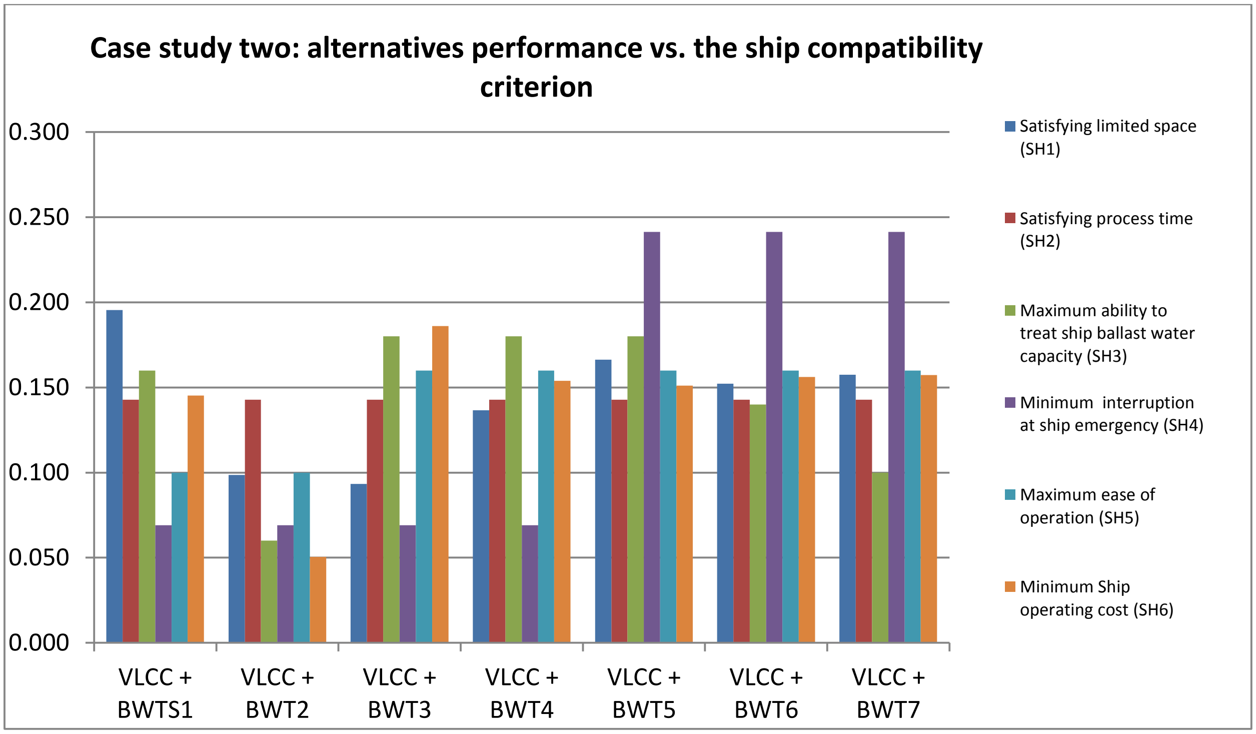

Figure 7-25: Alternatives performance based on the ship-compatibility criterion in case study two

The obtained findings as shown in Figure 7-25 can be summarised below:

- VLCC+BWTS3 alternative (0.186) is the most preferred alternative to minimum ship operating cost. This is not different than case study one as expected.
- VLCC+ BWTS5-7 alternatives are the most preferred alternatives to the minimum interruptions at ship emergency criterion (0.241). This is not different than case study one as expected.

- All the alternatives equally have satisfied process time criterion (0.143). This result is different from that in case study one. This is due to the assumption of the prolonged voyage which enabled all the alternatives to have enough time in order to effectively and efficiently treat the ballast water.
- VLCC+ BWTS1& 2 alternatives weighted less amongst other alternatives towards the maximum ease of operation criterion (0.100). This is not different than case study one as expected.
- VLCC+ BWTS3, 4 &5 alternatives are the most preferred alternatives towards the maximum ability to treat ship ballast water capacity (0.180). This is not different than case study one as expected.
- VLCC+BWTS1 alternative is the most preferred alternative that satisfies the limited space criterion (0.195). The result is not changed as expected.

It should be noted that some scores were expected to remain the same because in case study two only the voyage length has been altered and thus it should have only altered the performance of the alternatives with regards to time. It is shown that the temperature and other parameters have not changed and thus the rest of the parameters should remain unchanged as expected.

By combining all the new facts in Figure 7-25, along with the priorities obtained from the decision maker about the importance of each of the ship compatibility indicators, the results are shown on graph in Figure 7-26.

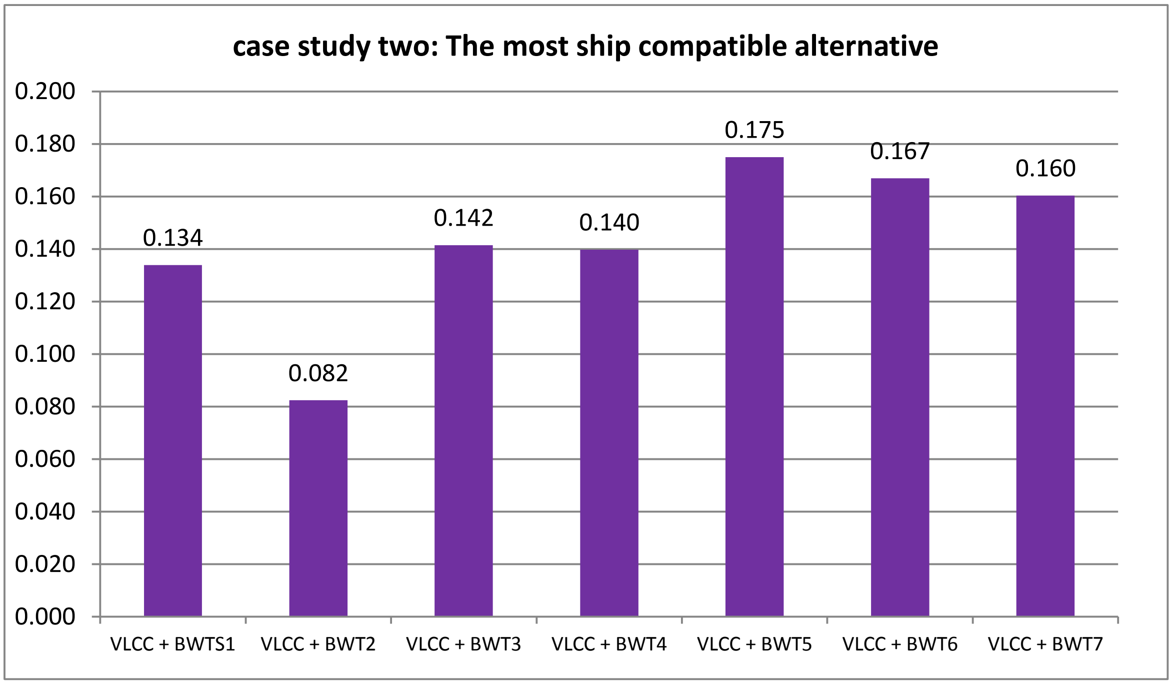

Figure 7-26: The alternatives order after combining decision maker's importance for ship compatibility criterion in case study two

In Figure 7-26 the VLCC+BWTS5 alternative remained the most preferred alternative (0.175) for the VLCC based on the decision makers input preferences. The result shows a small decrease which affected them as expected. This is because VLCC+BWTS5 lost some of the scores in satisfying the process time when all the rest of the alternatives equally have scored higher than that in case study one. This is due to the longer voyage duration that implied more available time and thus more ability to treat ballast water capacity by the required time for all the given alternatives. In addition, because VLCC+BWTS5 alternative scores towards the ship compatibility has been unchanged i.e. satisfying limited space and the maximum ability to treat ship ballast water capacity criteria amongst all the given alternatives. This has supported VLCC+BWTS5 alternative to remain higher than the rest of the given alternatives. However, although VLCC+BWTS5 scored less for satisfying the minimum ship operating cost than VLCC+BWTS6&7 alternatives, this has not significantly changed the results because this criterion was not given a significant weight by the decision maker. Therefore, based on combining all these scores the model selected VLCC+ BWTS5 over the rest of the given alternatives.

Next sub sections, more details of how results were obtained about the sub-criteria for the ship compatibility are presented.

7.2.3 Satisfying process time (SH2)

The comparison of the limited space criterion between the alternatives was based on satisfying the ship operating mode and satisfying ship voyage length sub-criteria between each of the seven BWTS alternatives.

Based on aggregated data of each BWTS alternative as presented in chapter 5. The derived results are shown in Figure 7-27. With longer voyage time i.e. 24 days all alternatives are assumed to effectively satisfy both ship operating mode and voyage length criteria.

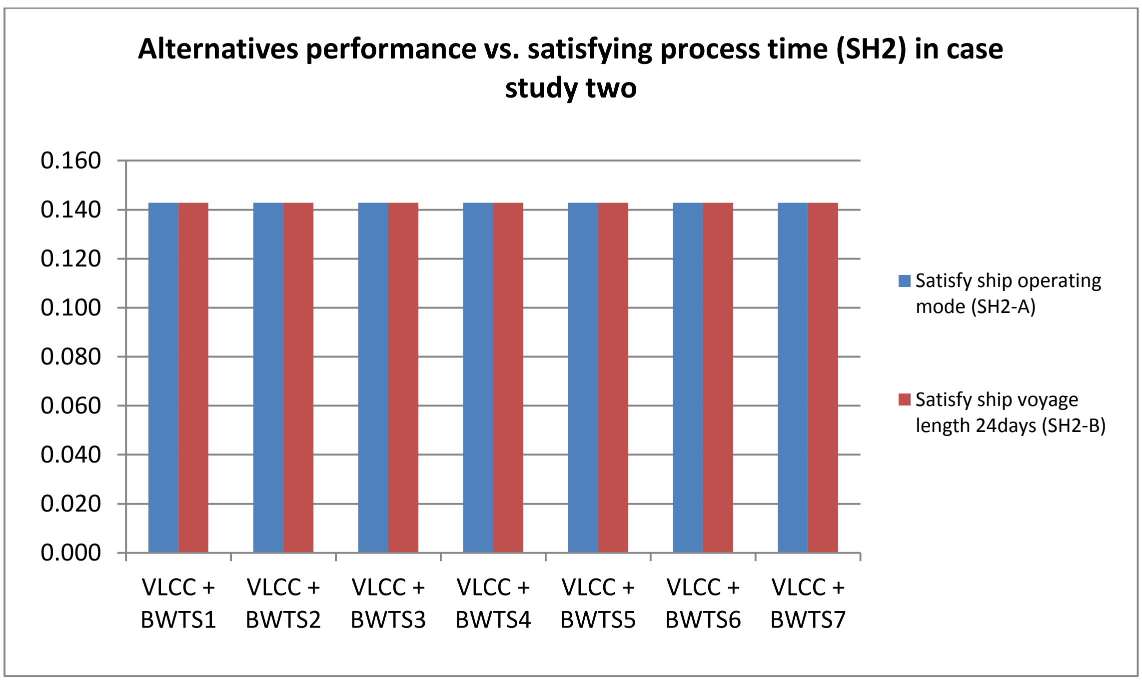

Figure 7-27: VLCC+BWTS alternatives performance vs. satisfying ship operating mode and voyage length in case study two

7.2.4 Synthesising the outcome based on case study two

Synthesising the combined vectors of priorities for satisfying the global criteria between each of the seven BWTS alternatives are shown on the graph in Figure 7-28.

In Figure 7-28 the key finding are summarised below:

- VLCC+BWTS1 alternative (0.225) is the most preferred alternative to the safety criterion as expected.
- VLCC+BWTS3 alternative (0.231) is the most preferred alternative to the cost criterion as expected.
- VLCC+BWTS5 alternative (0.175) is the most preferred alternative to the ship compatibility criterion as expected. However, there is a little change in the score because the other alternatives shared equal scores on the ship compatibility criterion as discussed in the previous section. Nevertheless, the order of the alternatives remained the same as for case study one as expected.

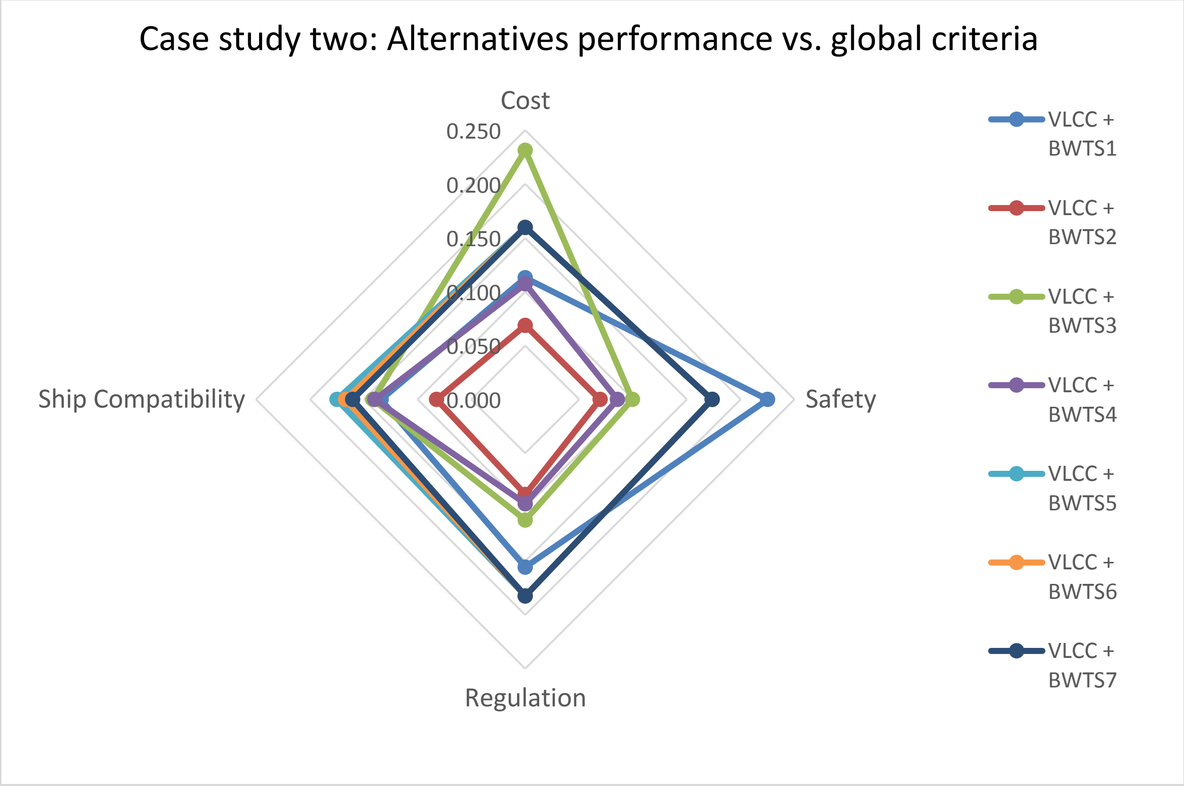

Figure 7-28: BWTS-VLCC alternatives performance vs. the global criteria, case study two

Combining all these facts in, Figure 7-28, along with the priorities obtained from the decision maker about the importance the global criteria; the outcome from case study two about the most feasible alternative is shown on the graph in Figure 7-29.

In Figure 7-29, the VLCC+BWTS5 alternative (0.1780) remained as the most feasible alternatives for the given VLCC as expected. This is because VLCC+BWTS5 alternative scored more than the rest of the given alternatives for the identified criteria. However, it can be argued that VLCC+BWTS5 alternative did not score better for the cost criteria than VLCC+BWTS3. Yet the cost criterion was not given sufficient weight by the decision maker. In addition, according to the sensitivity analysis Table 7-2 and the sensitivity test to the highest capital cost, the cost alteration have been proven by the conclusion derived from Table 7-2 about changing the cost as expected. It was found that the cost is an insignificant criterion that can alter the selected alternative by the model for this particular decision maker and VLCC.

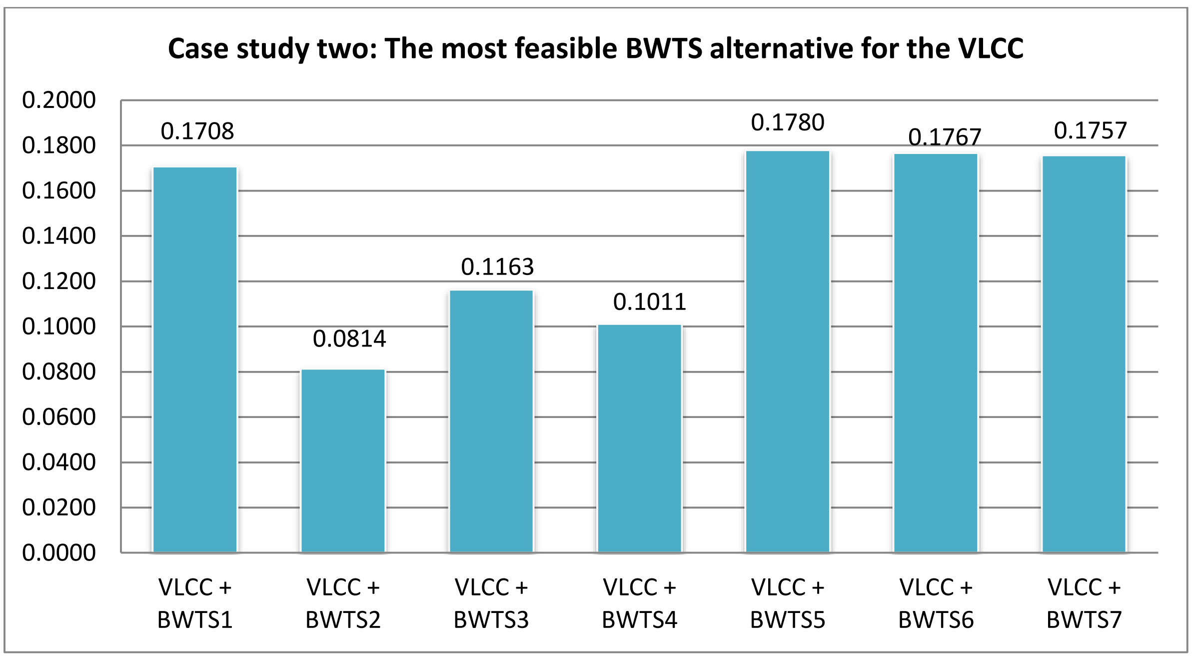

Figure 7-29: The alternatives order after combining decision maker's importance global criteria in case study two.

On the other hand, VLCC+BWTS1 alternative (0.1708) has been shown as the most feasible alternative after the three VLCC+BWTS5-7 alternatives. This is because VLCC+BWTS1 alternative scored better than the rest of the given alternatives towards the safety criterion. However, it scored less by the rest of the identified criteria as shown in Figure 7-5.

It is worth noting that the outcome of case study two with changing the length of the voyage of the VLCC has not altered the selected alternative for the VLCC as derived from the sensitivity analysis of case study one as expected. Therefore, the alternative test (**H_1**) is rejected. The derived results from case study two and the sensitivity analysis performed in this chapter have validated the applicability of the model to help decision makers selected the most feasible BWTS for their ships.

7.3 Model validation

Validation is a sophisticated process because of the subjective judgments to the reasonable degree of what is considered a good enough concept, and this indeed differs from the point of view of different individuals. The problem is that subjective judgments can make the validation of an approach, theory or models to be considered impossible. On the other hand, it is also impossible to eliminate the subjectiveness from our judgments. Therefore, a model is normally validated by testing to identify whether or not it does what it is supposed to do and whether the solution offered by the model makes sense.

According to Collis and Hussey (2003), methodologies or mathematical models are like theories that cannot be verified or falsified, but are more or less useful. Therefore, a methodology or mathematical model should always be accepted, given that there are not enough evidences to reject it.

As a general approach, a model can be possible when is validated by comparing the output obtained by the model with historical output data or predicted models. However, there are no universal criteria or standards to validate models because any validity judgments involve subjective beliefs and this get us back to the same circle. The validation of a decision model is possible by justifying three key points (Firouzabadi, 2005):

1. Methodology validation

2. Mathematical model validation
3. Outcome of the model validation.

Therefore, the validation of the model will be discussed next in this chapter.

7.3.1 Methodology validation

The methodology used in this thesis is based on a well-known MCDM method named AHP which is used in thousands, if not more, academic researches and PhD theses, industrial and governmental organisations (see chapter 3 for more information).

In addition, the methodology used the tangible (or objective) and intangible (or subjective) data for the three inputs based on real sources of information through: interviews with 12 experts from three different trade shipping companies, whom had also evaluated the importance of each identified criterion used by the AHP model; judgments (or preferences) obtained from a decision maker through a web-based criteria weighting questionnaire from a well-known shipping company on the identified criteria; actual data were also obtained from the BWTS vendors websites or catalogues of each BWTS; the missing data were approximated based on the information of relevant literature; Ship particulars of the VLCC and voyage data were obtained by a well-known shipping company.

Moreover, the methodology is simple and easy to use and produce accurate results because all the steps of eliciting judgments were based on pairwise comparisons using the traditional AHP method. The decision maker had no problem to complete the questionnaire and thus no further requirement to re-construct the model. Inconsistency ratio of all the pairwise comparisons had satisfied the less than 10 percent cut-off line as suggested by Saaty (1980). Due to some difficulties in obtaining response by the decision maker, some preferences or judgments have been found inconsistent. However, this is not a serious issue because the sensitivity analysis has dealt with the issues of imprecise judgments by the decision maker. The latter, implies satisfying judgments which were obtained.

Finally, the methodology is considered flexible, as it can be used by a single decision maker, i.e. used in this study, and multiple decision makers. Moreover, both tangible and intangible data can be included to obtain the output.

7.3.2 Model validation

Firstly, the model was evaluated through the interview with 12 experts from three different trade shipping companies. Based on their experience, they evaluated the importance of the criteria and indicators and it was concluded that this model can be considered as a tool for selecting the most feasible ballast water treatment system.

Secondly, the model was developed using Microsoft Excel, and then reconstructed using the Expert Choice software. The outcomes between the two have small percentage of difference up to a maximum of 6% at BWTS4 alternative. However, as discussed earlier in this chapter, this small change in percentage is not a serious one i.e. giving totally different results, but it is a result of different methods employed for normalising an AHP mathematical matrix to obtain the vector of priorities as presented and discussed by Saaty (1980). Therefore, the differences are not considered serious because they have provided the same outcome orders to the BWTS alternatives as shown in Table 7-1. Therefore, the model is reliable.

Although, some criteria of the alternatives involved subjective judgement and a bit of guesswork as well, the output of the model had no surprises to the model developer. In other words, the outcome made sense and the derived results were intuitively acceptable. In addition, sensitivity analysis by changing criteria priorities on the decision variable to see whether the output of the model behaves in a plausible manner and that has been found valid. Therefore, the output of the model did not include surprises as expected.

7.3.3 The outcome validation

In this research, the construction of the problem involved evaluating the derived results in case study one by the sensitivity analysis and robustness test which was tested into case study two for the same VLCC. Based on the concluded sensitivity analysis of results of case study one Table 7-2, two robustness tests were put forward, a null test (**H_0**) and an alternative test (**H_1**) stating:

- **H_0:** with all other criteria remains the same for the VLCC. Changing the priorities of the ship compatibility criterion by changing any of its sub criteria (indicators) such as satisfying length voyage criterion through changing the ship's voyage length, the outcome of the model **will not alter** the selected alternative.
- **H_1:** with all other criteria remains the same for the VLCC. Changing the priorities of the ship compatibility criterion by changing any of its sub criteria (indicators) such as satisfying length voyage criterion through changing the ship's voyage length, the outcome of the model **will alter** the selected alternative.

The outcome of case study two revealed that no alteration to the selected alternative VLCC+BWTS5 for the VLCC as stated in case study one as expected. The alternative test was rejected. Therefore, this result has validated the applicability of the model to help decision makers selected the most feasible BWTS for their ships. The model was able to identify with 100% accuracy, as expected, that if the ship compatibility criterion had changed, while all other criteria and alternatives remained the same, the selected alternative will remain the most feasible one for the VLCC. The conclusion derived from sensitivity analysis Table 7-2 about the cost criterion was also examined by considering the highest capital cost for its ability to alter the selected BWTS alternative or not. The outcome of the model revealed no alteration to the selected BWTS alternative as expected. This has increased the validity and the applicability of the model because it was found in 100% agreement with conclusions derived from the sensitivity analysis in Table 7-2 as expected.

The intention of the model is to help decision makers select the most feasible BWTS for their ships. In addition, it could also aid researchers in understanding the relationships between the different processes and their consequences on their BWTS selection. Therefore, to increase the validity of the obtained results by the model, an interview with decision makers from a well-known shipping company were conducted during the first week of February 2015 for their opinions on the results obtained by the model. This is discussed in details next.

7.3.3.1 Validation interview with decision makers from a well-known shipping company

The interview was arranged by making phone calls with a decision maker by sending emails to the responsible senior staff personnel and manager who is responsible about the BWTS alternative selection for company's ships. Therefore, this interview and presentation were conducted with the appropriate decision makers who hold on authority or knowledge to make decisions on the selection between BWTS for their shipping companies.

Before the interviews, emails were sent to the decision maker explaining the ultimate aim of the interview and the type of questions which will be asked after the interview and the presentation. The objective of the interview was to acquire the opinions of the decision makers from the shipping company on the outcome or results obtained by the developed model.

The interview presentation is divided into seven sections. Section 1 presented the Novel AHP Model; Section 2 consists of short snap shots of the three source of information/ data collected as inputs to the model and graphs showing how data were interpreted into the model; Section 3 consists of the results of case study one and the performance of each BWTS alternative under the defined criteria considered for comparing between all ballast water treatment systems alternatives; Section 4 consists of the sensitivity analysis performed by changing the relative importance of each criterion and sub-criterion in order to find out the most sensitive criterion table and performance graphs; Section 5 presented case study two of the same VLCC under different voyage; Section 6 consisted of results of case study two graphs and BWTS alternatives under each criterion; Section 7 consisted of the conclusions of the presentation noting the results obtained by the model in case studies one and two, the sensitivity analysis. The copy of the validation questions are presented in Appendix C.

The interview was conducted with two experts namely the Superintendent Engineer Senior Specialist of the Fleet Engineering Group and the Team Leader Fleet Engineering Group. Therefore, the interviews were conducted with the key responsible personnel or experts from a well-known oil shipping company in order to seek validation of the results obtained by the model.

7.3.3.1.1 Analysis of the interview results validation questions

The interview was conducted at the company's head office. The interviewer was welcomed in a very professional and friendly environment. The interview began immediately after the arrival to the office in order to prevent interruption the busy time of the experts. Before proceeding to the presentation, the interviewer explained the aim of this interview stressing on the purpose of sharing their opinion on the applicability of the model as a decision support tool to assist shipping companies to select the most feasible ballast water treatment system for their ships. After giving an internal presentation to the two experts, and conclusions of the presentation, the experts were shown eight interview validation questions. The details of the questions and answers were hand note taken during the interview as follow:

In the first question the interviewees were asked "*1- Does the presented results show the applicability of the model as a helpful tool?*" Both experts answered very quickly and very excited "*Yes*".

The second question the interviewees were asked "*2- Please explain your answer of the above question*?" One expert responded: *"The tool, provided a credibility to explain and show why the BWTS alternative was selected and in clear way of convincing other team leaders and decision makers in the company*". Second expert responded: *"definitely useful and unique, because it is simple and clear why the selections were made*".

Third question the interviewees were asked "*3- Do you think that the results obtained by the model were useful?*" Both experts answered "*Definitely yes*".

Fourth question the interviewees were asked "*4- Why do you think that the obtained results are useful or not useful?*" One expert answered: *"Useful, because this will support* *decision making in comparing various parameters by given it a proper weight or scores which made the method easier to use for making decisions*". The second expert answered: *"decision makers in the company can use this tool during their investigations and studies to ballast water treatment systems in order to finalise decisions on the selected BWTS for their ships*".

The fifth question the interviewees were asked*: "Have the obtained results matched what was selected or installed into this VLCC?"* One decision maker answered:" *yes, matched the selected UV BWTS alternative in 100%, but 98% on the vendor*". The second expert answered:" *Matched the UV disinfection approach, but not the exact BWTS vendor*".

The sixth question the interviewees were asked*: "If not, why do you think the selected was different?*" One decision maker answered: "*actually I would say yes for this question, but not the same vendor because of the different criteria which were used by the company for short listing the BWTS suppliers. For example, one of our criteria is that the BWTS vendor must have installed his BWTS into at least 10 similar ships, and if he has not then he will be excluded".* The second decision maker answered: *"little different because of the criteria which were used internally by our oil company*".

The seventh question that the interviewees were asked: *"7- Do you think that this model can be easily implemented as tool to help you select the most feasible BWTS alternatives for your company's ships?"* Both decision makers answered: *"Yes indeed, because it has simplified the BWTS selection process into very simple accurate tool".*

The eighth question that the interviewees were asked:*"8- Can you add any comments on the results?"* One decision maker answered: *"Other criteria can be added to the model such as vendor reputation, number of installations, global presence and spare parts, and USCG type approval"*. Second decision maker answered: *"This tool has a big dollar sign on it"*.

Based on the interview, experts were 100% satisfied by the outcome of the model.

7.4 Summary and conclusions

In this chapter, the sensitivity analysis was performed by using the developed decision support tool or model and finally to validate the applicability of the model, two robustness tests were put forward and then tested by case study two for the same VLCC under different voyage.

In chapter 6, the outcome of the model for case study one has selected VLCC+BWTS5 (0.180) as the most feasible alternative of the VLCC. However, the outcome of the model had many uncertainties regarding the results due to the possible errors for the different reasons. Thereafter, in this chapter, the sensitivity analysis of the criteria was performed based on the changes of the relative importance of criteria and sub-criteria in order to find out which of them is critical and need to be carefully considered by the decision maker. The sensitivity analysis has informed that the outcome of the selected VLCC+BWTS5 will remain the most feasible alternative amongst the given alternatives for this VLCC even if the priorities were changed. On other words, any changes in the priorities of the cost and regulation can be considered critical, yet it is unlikely to cause any alteration to the selected alternative for this VLCC. On the other hand, the ship compatibility criterion was indicated as a significant criterion that can implies changes of the alternatives, yet with a little possibility to alter the selected VLCC+BWTS5 alternative for this VLCC.

Based on the derived information from the sensitivity analysis, two robustness tests were put forward a null test (**H_0**) and an alternative test (**H_1**) stating:

- **H_0**: with all other criteria remains the same for the VLCC. Changing the priorities of the ship compatibility criterion by changing any of its sub criteria (indicators) such as satisfying length voyage criterion through changing the ship's voyage length, the outcome of the model **will not alter** the selected alternative.
- **H_1**: with all other criteria remains the same for the VLCC. Changing the priorities of the ship compatibility criterion by changing any of its sub criteria (indicators) such as satisfying length voyage criterion through changing the ship's voyage length, the outcome of the model **will alter** the selected alternative.

In order to test the above two robustness tests, the model redeveloped in case study two, and results from both case studies (one & two) are compared for any possible changes of the selected alternative. In case study two, the VLCC unload cargo in Huizhou (China), fill in ballast water tanks in order to maintain the required safe operation under various weather conditions by adjusting the trim while maintaining the optimum speed of the ship before it reach Angola port (South Africa) fully ballasted. In this leg, the VLCC got 24 days to reach back to Angola in order to load cargo.

It is worth noting that the VLCC's loading location was changed and thus lengthened its voyage duration from 14 days (case one) into 24 days (case two). This means all the other criteria remained the same as in case study one; however, the priority of the ship compatibility criterion has been altered.

The outcome of case study two has not changed the selected alternative for the VLCC as stated by the sensitivity analysis of case study one as expected. Therefore, the alternative test ($\mathbf{H_1}$) is rejected. At this point, the derived result has validated the applicability of the model to help decision makers to select the most feasible BWTS for their ships.

In this chapter, it was discussed that it is very difficult to validate any given model if it's not impossible. However, the validation can be made through justifying that there was not enough evidences to reject it. The combined justifications of the validity to the methodology, to the model, and to the outcome of the model, this chapter submits that there are no enough evidences to rejects the model. In addition, as one step to increase the validity of the model, an interview with experts or decision makers from a well-known shipping company was conducted. The output of the two case studies derived by the model and the sensitivity analysis was internally presented and finally the validation questions were asked during the interview. The model and its outcome was 100% satisfied by both the decision makers who find that this model provide 100% match to what have been selected for the given VLCC and 98% in the vendor. Therefore, the chapter also submits the applicability and validity of the model as a tool to help decision makers select the most feasible BWTS for their ships.

Chapter 8 gives an overview of the research summary, objectives achieved, novelty and contribution to knowledge of this thesis, and limitation and the future research recommendations.

Chapter 8: Concluding Remarks

8.0 Introduction

In this chapter, the summary of the research and key contributions and novelties are discussed first. Thereafter, the accomplishment, the limitations which were encountered during the research, the publication, and the recommendations for future research are discussed. Finally the conclusions of this thesis are outlined.

8.1 Summary

In this research, both the ship related parameters and the ballast water treatment system (BWTS) related criteria that influence decisions on the selections of BWTS were collected from the literature review. These criteria were investigated and validated in a case study through interviews with twelve experts from three different trade shipping companies. In the interviews, the issue with the selection of the most feasible ballast water treatment systems was discussed, including information of the criteria that could be used for the decision tool, the existence of a tool or software that is used by shipping companies to help them select the most feasible BWTS for their ships were discussed in Chapter 4. During the interviews, experts had evaluated the importance of the identified parameters which can be used as a tool for supporting decision makers in selecting the most feasible BWTS. Only the important criteria, according to the experts, were used in the decision support model. These criteria formed the hierarchy structure of the AHP decision support model, at the other end of the structure seven BWTS alternatives were connected and pairwise compared to satisfy each of these criteria in a hierarchy structure. Starting from the goal (level one), each criterion is also pairwise compared with respect to other criteria by the decision maker from a well-known shipping company. It is worth noting that slight amendments to the model have been done based on the expert’s opinion before using the model into actual case studies.

Based on the evaluations from the decision maker on each criterion and the evaluations made from the information obtained by the BWTS vendor’s websites or brochure’s and the relevant literature review for finding the missing data, the outcome of the actual case study one was successful. The sensitivity analysis, robustness tests, case study two, and interview with experts had enabled the validation of the developed model and its outcome, and its applicability to help decision makers to select the most feasible ballast water treatment system for their ships.

This thesis can be summarised by its eight chapters listed as follows:

- **Chapter 1**: Provide an overview of the research study background and motivation, clearly defining the aim, the objectives, and the structure of this thesis.
- **Chapter 2:** This chapter presents an overview on ship's ballast water, marine vehicles and the relevant studies of the selection of the best ballast water treatment system. In this chapter the gaps has been identified and the problem statement has been discussed leading to the goal of this thesis and the aims that need to be achieved.
- **Chapter 3**: This chapter provides an account of the author's considerations with regard to the selection of the appropriate methodology and the overall research design for this study. This chapter considers the different elements about research methodology, paradigm (qualitative or quantitative or both) and researcher's assumptions. Then it argues the consideration and methodology employed in this study. Two most popular MCDM i.e. Multi-Attribute Value (or utility) theory and The Analytical Hierarchy Process (AHP) were compared for their similarities and thus selected AHP as an appropriate MCDM method in this study.
- **Chapter 4:** This chapter provides the first data collection and analysis process and a detailed overview of the case study with 12 experts interviews from three leading different trade shipping companies. The issues of the ballast water, the importance of the selected criteria, the lack of existing decision tool in shipping companies, and the amended structure of the developed model which has been slightly modified, are discussed and presented in this chapter.
- **Chapter 5**: This chapter focuses on how the research method is applied into actual case study. The data collection and evaluation based on actual data

requirement for the developed model, are discussed. In this chapter, three sources of data were needed namely: data of a ship and her voyage; technical parameters for each of the selected Ballast Water Treatment Systems (BWTS) alternatives; and decision maker evaluations for the relative importance of each identified criteria in the decision support tool. Details on the needed information collection and evaluation are presented and discussed in this chapter.

- **Chapter 6**: This chapter presents details on the outcome or the results from the decision tool based on the input data acquired from Chapter 5. In this chapter, there was no surprises were experienced and the outcome of the model was found intuitively acceptable. However, due to many uncertainties of the inputs data, more analysis and investigation were required for the applicability and the validity of the model.
- **Chapter 7**: This chapter can be considered as the validation chapter. The sensitivity analysis of the developed model was performed to validate the applicability and the sensitivity of the model to the changes of the priorities of each criterion. Ship compatibility criterion was found as the most critical criterion which may, with little possibility, alter the selected alternative. Based on the latter information, two robustness tests were put forward in order to validate the applicability of the model. In order to test the latter, case study two were developed by changing the voyage duration and trade route of the VLCC in order to test whether this would alter the decision on the selected alternative or not. The outcome of case study two did not change the selected alternative for the VLCC in case study one as expected. Therefore, the alternative test was rejected. This chapter argued the validity of the proposed model and the outcome by answering three important questions:
    - Why the methodology used in this thesis is valid?
    - Why the developed model is valid?
    - Why the outcome of the model is valid?

  It was argued that it is very difficult to validate this model or any other model. However, the validation of the developed model was based on justifying that there are not enough evidences to reject it. An additional validation step is gained by interviewing two decision makers of a well-known shipping company on the outcome of the model which were 100% satisfied by the model and its outcome.

- **Chapter 8**: This chapter is considered as the conclusion of this thesis. It also provides a summary of the approach adopted in this research, presents the accomplishment of the research process, and describes where aims are achieved. In addition, the thesis contributions and novelties were presented; the limitations which were encountered during the time of this research and recommendations for future research are discussed.

In addition the following appendices are provided:

- **Appendix-A**: The questionnaire used to interview experts for the purpose of this study is presented.
- **Appendix B**: The survey named 'criteria weighting questionnaire' is attached.
- **Appendix C:** The validation's questions of the interview are presented.
- **Appendix D:** AHP analysis and the implementation in Microsoft Excel are presented in detail.
- **Appendix E:** The Fuzzy Analytic Hierarchy Process (FAHP) application study to the 1st model is presented.

8.2 Key contributions and novelties

The key contributions and novelties of this research can be outlined as follows:

- This study is the first study that develops an AHP model as a tool for selecting a ballast water treatment system, which considers both the ship and the ballast water treatment systems parameters/criteria. In specific, the ship compatibility was considered, which was divided into six sub-criteria/parameters namely: satisfying limited space (SH1), satisfying process time (SH2), maximum ability to treat ship ballast water capacity (SH3), minimum interruption at ship emergency (SH4), maximum ease of operation (SH5), and minimum ship operating cost (SH6). It is important to note that, each of these six sub-criteria have been evaluated through identified sub-sub-criteria/parameters as follows: satisfying limited space (SH1) is evaluated by using three indicators namely: compact as one unit (SH1-A), can be installed in a hazardous place (SH1-B), and minimum requirement to additional equipment (SH1-C); satisfying process time (SH2) is evaluated by using two indicators namely: satisfy ship operating mode (SH2-A), and satisfy ship voyage length (SH2-B); and minimum ship operating cost (SH-6) is evaluated by using four indicators namely: minimum requirement for extra expertise (SH6-A), minimum requirement for crew training (SH6-B), minimum fuel consumption (SH6-C), maximum ease for maintenance (SH6-D).These parameters/criteria that can provide additional insight of the selection process were not considered in the previous works, where only the ballast water related criteria were used.

- The research has been accomplished through the following novel approaches:
    - Identification of parameters or criteria that influence decisions on selecting a ballast water treatment system for a given ship by using a thorough literature review, experts' interviews and analysis of the experts' evaluations. This was not reported in the previous works. The thorough literature review contributed to the identification of the used criteria related to the ballast water treatment systems as well as the ship parameters/criteria. The latter were not considered in the previous studies. The interviews included twelve experts from three different shipping companies who evaluated the importance of the identified criteria and structure of the model as a tool for selecting the most feasible BWTS for the ships. The views and the opinions of the shipping companies' experts were not considered in the previous studies.
- Development of a systematic methodology for selecting the most feasible BWTS for the ships. This was not considered in the previous studies where the process of selecting the most feasible BWTS for ships was based on an approach of focusing only on BWTS parameters and neglecting other important criteria identified in this work. The proposed methodology provides the decision makers the ability to measure their priorities and to evaluate the importance of changes of their initial decisions and/or criteria.

- Testing the developed model in such case studies were not considered in the previous works. Therefore, this study contributes to towards highlighting the importance of the involved parameters interdependencies in actual test cases selection process.
- Validation of the developed model by using sensitivity analysis, robustness tests, and experts or decision makers' evaluations. This was not considered in the previous works where the usage of sensitivity analysis, robustness tests, and experts or decision makers' judgments have not been reported.

As a conclusion from the above, the thesis contribution to the knowledge/research in this field is regarded as essential.

8.3 Accomplishment of research objectives

In this research, the following objectives have been achieved in Table 8-1.

Although the evaluations of the model have been constructed by focusing on a particular issue of selecting between seven BWTS alternatives for a particular VLCC under specific trade route, it is clear that the concept and the method could be easily generalised and duplicated.

Table 8-1: Thesis objectives and where have been achieved

no	objectives	Methodology	Achieved
1	To identify the influencing parameters and/or criteria related to both ballast water treatment system and ships parameters.	Literature review + case study- Interview with 12 experts from three shipping companies.	Completed in the literature review Chapter 2 and the Interview case study chapter 4
2	To evaluate the importance of the selected criteria for both BWTS and ship parameters criteria.	Literature review + case study- Interview with 12 experts from three shipping companies.	Completed in the Interviews with 12 experts (expert interview case study chapter 4)
3	To apply an appropriate Multi-Criteria Decision Making (MCDM) technique along with the above points.	Completed in the methodology chapter 3, and finalised the model in chapter 4.	
4	To validate the developed decision support tool and investigate its applicability in actual case studies.	Completed in chapter 6 &7 i.e. case study one, sensitivity analysis of the outcome, robustness tests, case study two and experts interview from a well-known shipping company on the outcome and the developed model.	

8.4 Limitation of the research

The limitation experienced during this research for the development of a tool or a model to help decision makers to select the most feasible ballast water treatment system for their ships can be summarised as follows:

- Due to time and cost constraints, this thesis has provided a study for understanding how the selection of a ballast water treatment system can be influenced by many factors or criteria. However, the lack of available data/information to support this study by the ballast water vendors requires more investigation for a full understanding and appreciation of the selection process.
- Some criteria were emphasised by the experts such as BWTS vendor quality or reputation and were not included in the model because of the time constraint and limited budget to investigate the issue for more understanding of its applicability as a limiting factor. In addition, some criteria were not found significantly important according to the expert's evaluations, and thus were not used in the developed model of this study.
- The AHP pairwise comparisons for all the given alternatives were found an easy process to follow, but a time consuming one. On other words, when the number of criteria and levels of the hierarchy increase, more time is required for pairwise comparisons which can make this approach tedious. In addition, this was particularly present when objective data of some criteria were not readily available and thus researching literature to find the missing data or other approaches was necessary in order to complete the study. On other words, subjective judgments or evaluations required more assessments and time than objective data to achieve results.
- Retaking surveys for the evaluation by the decision maker was found a difficult process. This is because, the decision maker was found to be friendlier when providing him with new answers or solutions rather than repeating surveys or being re-interviewed.
- Interviewing experts face to face was considered a brilliant way to gain information's and opinions of a particular knowledge or a subject that is sensitive or highly confidential. However, interviews were not found an easy task for the following reasons:
    - Experts had holidays and the researcher needed to wait for their responses in order to confirm the time and date of the interview. Although, when time and date were agreed on, experts had changed the time due to their

busy schedules. Therefore, longer time was taking to accomplish the interview’s aim.

- This approach required a high level of knowledge on the subject by the researcher before interviewing the experts in order to enable the collection and the summarising of the necessary information collated from interviews.
- Interviewing experts from shipping companies was found more costly and time consuming. The researcher required to purchase flying tickets, making international phone calls, agreeing on the time/date of the interviews, and traveling in order to meet experts.
- One of the main limitation of the interview was the language barrier. This is because, some experts declined to be interviewed in English.
- Notes were taking during the interview, and thus the researcher rarely had time to make crucial eye contact.
- The researcher required to think deeply into what are the important questions that needed to be asked, and the process of developing the questionnaire also required to follow particular skills:
  - Questions must be well-presented and easy to read and follow.
  - Vague words should be avoided. More explanation by providing definitions was found a good way to reduce such problem.
  - All questions needed to be checked by supervisors for its professional appearance and ethical appropriateness, and that required more time and effort for re-writing the questions.

8.5 Publications

As a result of the research carried during its time, two conference papers were successfully published which presented the developments of the decision support model as new tool to BWTS’s selection as listed below:

- ALHABABI, H. H. M. H., THEOTOKATOS, G. & TURAN, O. 2014a. Analytical Hierarchy Process for matching a ballast water treatment-VLCC Marine and Offshore Engineering Technology Conference MOETC. Kuwait.
- ALHABABI, H. H. M. H., THEOTOKATOS, G., TURAN, O. & BELTON, V. 2014b. A Novel AHP Model for Selecting the Most Feasible Ballast Water Treatment for a Bulk Carrier International Conference on Maritime Technology ICMT. GLASGOW, UK.

The above listed papers have contributed to research in this field.

8.6 Recommendations for future research

Making decision is a complex task for selecting BWTS because of several factors involved, tangible and intangible data which affect the way of making decisions. Future recommendations can be advised as follows:

- The proposed approach looked at the problem in a deterministic way through the application of one MCDM, i.e. AHP method only for the selection between different BWTS alternatives. The application of the Fuzzy Analytic Hierarchy Process (FAHP) to the 1st developed model was applied due to its ability to achieve better results than using AHP alone if uncertainties were involved in the problem. However, the results obtained by using FAHP study revealed a great consistency with the results obtained by the 1st developed AHP model. Therefore, the author did not find applying FAHP would make better results if it was used for the final developed model. In addition, the sensitivity analysis have already underpinned the uncertainty issue with the imprecise judgments by the decision maker and their possible influences on the final results (FAHP study is presented in Appendix E).
- This model looked at the feasibility of selecting a ballast water treatment alternative for a particular VLCC. This model can be applied for different types of ships such as Liquefied Natural Gas (LNG) carrier or a container ship with consideration of different types of BWTS alternatives. This could have been done in this research, but due to the time constraint and budget, it was very difficult to

acquire more information from other shipping companies. It is worth noting that, the researcher contacted several shipping companies to provide information, but they declined to respond.

- This model can be re-developed focusing on a particular region or a country's ballast water standards for selecting the most feasible BWTS alternative. However, future studies may investigate the parameters that should be optimised in order to suit a particular ship or a region or any possible changes in future regulations and standards. For example, if the problem requires setting limits to some objectives, this model will require the use of other MCDM methods such as goal programming or linear programming combined with/without AHP.
- This research considered experts views from different trade shipping companies. However, future studies may consider the investigation involving other stakeholders such as experts from classification societies, ballast water vendors and ship yards in order to obtain more decision makers involved in selecting the most feasible ballast water treatment system.
- This approach can be researched differently from the marine science point of view on how to relate the bio-efficacy inactivation's of the various harmful organisms of a specific region or route on the selection of best BWTS.

8.7 Conclusions

There has been several conclusions derived from this research are summarised as follows:

- The review of the developed models in Chapter 2, showed that the selection of ballast water treatment systems is important and feasible approach to minimise risks with such a complex decision. Unfortunately, there are critical issues with the previous models such as the variation of the criteria which should be used from the selection between BWTS. It is worth noting that, one of the most important and critical factor for capturing the required information in models is the ability to capture the required data and evaluate inputs parameters, in order to generate the expected output. The latter is impossible without identifying the important criteria that form the structure of that model. Therefore, the need to identify the parameters and/or the criteria and their importance to select the most feasible ballast water treatment became very important step. This step was achieved in this research.

- For the development of a model, decision models in particular, the first step is the problem identification and structuring that involves the creative thinking which helps capturing the complexity of the problem as discussed in Chapter 3. Recalling, the goal of this thesis, i.e. to develop a decision support tool or model to aid decision makers to select the most feasible BWTS for their ships, therefore shipping companies has been selected as the required stakeholder in this study. Bringing the views and the experience of experts from shipping companies to the development of the model was found very useful in this research.
- The data aggregation of the necessary information and the approximations would influence the output of the model. However, the model was able to detect differences between similar types of disinfection alternatives. This implies that if the model had actual data from the BWTS vendors, it would had helped decision makers in shipping companies to compare between BWTS alternatives in a more deterministic way for selecting the best alternative for their ships.
- Some criteria and indicators were suggested by experts but were not added to the model even though they were ranked in the range (7 of 9). This is because adding more criteria would make the process tedious and difficult. In addition, this model was developed to capture the feasibility of selecting BWTS alternatives, but if the aim changed, more criteria are required to be considered by the model. Therefore, the model could be easily duplicated.
- The derived results by using the developed model showed no surprises to the user based on the inputs to the model. For example, the model was able to identify the best alternative under each criterion and this was very clear from the graphs presented in Chapter 6. It should be noted that, there are significant similarities in the scores between the selected alternative by the model, i.e. VLCC+BWTS5 (0.180) and the less scored alternative VLCC+BWTS6&7. These alternatives had very close scores and this may imply that these alternatives may require extra analysis because of the small differences between them. However, this was not

applicable in this study because VLCC+BWTS5, VLCC+BWTS6, and VLCC+BWTS7 alternatives were evaluated based on the subjective information which were aggregated from the literature based on their disinfection approach. If actual data were provided, more understanding would have been possible about these differences.

- The sensitivity analysis was very helpful method to understand the influence of the changes of relative importance of the criteria. It should be noted that, increasing the importance of the ship compatibility have selected the VLCC+BWTS5 as the most feasible alternative. This is because this alternative scored better than the other alternatives in satisfying the identified criteria in this model alongside the preferences of this particular decision maker.
- The outcome of the developed model was validated with 100% satisfaction by both decision makers and the robustness test as discussed in chapter 7. Therefore, this thesis submits the applicability and the validity of the developed model as a tool that can be used by shipping companies and operators to help them to select the most feasible BWTS for their ships.

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Appendix A

Stakeholder interview: Shipping Companies' view points

Dear Participant,

Today there are various ballast water treatment (BWT) technologies that claim to be effective in meeting the IMO Ballast Water Management (BWM Convention). It is worth noting that all these technologies vary in their approach to eliminate the harmful organisms, their environmental risks, safety, cost, processing time, capacity, etc.

This raises the question: Which of these ballast water treatment systems should a shipping company install into their ships?

This interview is part of a PhD research study on the design of a decision tool to assist stakeholders select the most feasible ballast water treatment system for any given ship. The aim of this interview is to aggregate aspects and opinions of the shipping companies about the criteria that should be taken into account when selecting a ballast water treatment system.

Your response by answering this interview questions will be of great benefit to the progress of solving one of the current important challenges confronting ship-owners and operators selecting the most suitable ballast water treatment system for their ships. Please note that your response will be kept strictly confidential. The answers will be used to develop a weighting criteria questionnaire, which finally will determine the input to the decision tool.

Thank you for your kind cooperation.

Kind Regards

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Interviewee	
Job title	
Organisation	
Date	
Tel	
Email	

SECTION A: INTRODUCTORY QUESTIONS

1 **Could you please describe your company and its main activities? (e.g. organisation chart, number of departments)**

2 **How many ships does your company operate/own; what is their size in deadweight tonnes and age?**

3 **What type of cargo is carried by your ships?**

4 **What are the destinations they sail to (geographic trading area)?**

5 **Approximation of annual volume of cargo transported (ports of loading/unloading).**

SECTION B: Ballast water treatment system

1 **From the environment perspective, how would you describe the importance for implementing a ballast water treatment system and meeting the International Maritime Organisation (IMO) ballast water convention?**

2 **What is your company future plan for meeting IMO ballast water regulation when it enters into force (e.g. using chemical inactivation; physical inactivation; ballast free ships)?**

3 **How much information have you obtained about the ballast water treatment systems?**

4 **Does your organisation have any concerns about these ballast water treatment systems?**

5 **What is the current ballast water treatment system used or intended to be used on-board your ships?**

6 **Does your company compare between the available ballast water treatment systems in order to select one?**

7 Which department in your company is responsible for comparing between the different ballast water treatment systems?

8 How many departments are normally involved in making that decision?

9 What are the procedures that need to be made when selecting the ballast water treatment system?

10 Does your company use any model, tool or software to assist selecting a ballast water treatment system?

11 Would you find it useful to have a decision making tool to help your company selecting the most feasible ballast water treatment system for each ship?

12 Please give reasons for your opinion?

SECTION C: THE PARAMETERS CONSIDERED FOR COMPARING BETWEEN BALLAST WATER TREATMENT SYSTEMS FOR A GIVEN SHIP

1 In case you use a specific tool or model, which parameters are used for the comparisons between the ballast water treatments systems?

2 If your company do not have a specific tool, then which parameters should be used in your opinion?

3 The identified criteria and indicators are listed in the table below (definitions are provided in the last page). Can you comment from (1-9) on the importance of each criterion?

Identified criteria	Indicators
6. Cost	• Minimum capital cost • Minimum operating cost • Minimum maintenance cost
7. Safety	• Maximum environmental safety • Maximum ship safety • Maximum crew safety
8. Bio-efficacy	• Minimum effect to change of seawater temperature • Minimum effect to change of seawater salinity • Minimum effect to change of seawater chemistry • Minimum effect to change of seawater clarity
9. Regulation	• Meeting IMO standards • Meeting other states standards
10. Ship compatibility	• Satisfy limited space • Satisfying process time • Maximum ability to treat ship ballast water capacity • Minimum interruption to ship emergency system • Maximum ease of operation • Minimum ship operating cost

4 Can you list any other criteria and indicators that should be taken into account when selecting between ballast water treatment systems?

5 Do you consider the above criteria should be used as a measuring tool for selecting between ballast water treatment systems for any given ship?

SECTION D: ADDED SHIP RELATED PARAMETERS

1 **The added ship related criteria are listed in the table below (definitions are provided in the last page). Do you think that these criteria are relevant to affect the decision of selecting a ballast water treatment system?**

2 **Can you comment from (1-9) on the importance of each criterion?**

Ship related criteria	Indicators
3. % of ballast leg	• Percentage of sea time cargo loaded per year • Percentage of sea time empty cargo run per year • Percentage of port time per year • Percentage of dry dock (for maintenance) time per year
4. Ship Age	• New (e.g. 1-8 years) • Middle aged (9-15 years) • Old (e.g > 16 years)

3 **Do you consider that these criteria should be used as additional measuring parameters for selecting between ballast water treatment systems?**

4 **Can you add any additional ship related criteria and indicators that should be used for selecting ballast water treatment systems?**

SECTION E: CLOSE

1 **Can you add any other useful information needed to develop a tool for selecting a ballast water treatment system?**

2 **Finally, what is the information/data that is not available and that you think will help you select a ballast water treatment system?**

DEFINITION

- **Cost** is monetary fees associated purchasing and installing a ballast water technology on-board a ship. The cost of a ballast water treatment system can be indicated by three aspects:
  - **Minimising capital cost** i.e. purchasing and installing fees;
  - **Minimising operating cost** e.g. cost associated with the technology power required;
  - **Minimising maintenance cost** i.e. associated with the routine & preventive actions for repairs, cleaning, replacing an item(s).
- **Safety** is the important role of being free of danger or risks. The safety of a ballast water treatment system for a given ship can be indicated by three aspects:
  - **Maximising environmental safety** i.e. risks to living environment when discharged;
  - **Maximising ship safety** e.g. corrosion to ballast tanks or hazardous to explosive space;
  - **Maximising crew safety e.g.** crew health.
- **Regulation** is the compliance with international maritime organisation (IMO) standards and specifically D-2 standards in addition to other states such as United States, Australia and Europe etc.
- **Ship compatibility** means the physical applicability of using a ballast water treatment on-board ship. Ship compatibility can be indicated by satisfying the following aspects:
  - **Satisfy limited space** is defined by the following indicators:
    - Compact as one unit, that means can be fitted in confined space;
    - Can be installed in a hazardous space
    - Minimum requirement to additional equipment e.g. pump, tanks, piping, storage etc.
  - **Satisfying process time** is defined by the following indicators:
    - Satisfy ship operating mode, whether follow a liner or tramp service, allows capturing the limited time for a ballast water technology to process in a given ship.
    - Satisfy ship voyage length, this depends on the ship speed as well to define the time required for a ballast water treatment system to process in a given time.
  - **Maximum ability to treat ship ballast water capacity** is defined by the following indicators:
    - Ship size can define the approximate ballast water system capacity.
  - **Minimum interruption to ship emergency system.**
  - **Maximum ease of operation.**
  - **Minimum ship operating cost** is defined by the following indicators:
    - Minimum requirement for extra expertise.
    - Minimum requirement for crew training.
    - Minimum fuel consumption
    - Maximum ease for maintenance
- **Bio-efficacy** is associated with the ability of a ballast water treatment to effectively reduce or/and eliminate harmful organisms from ballast water. However, studies found that bio-efficacy can be altered (or influenced) under the change indicators

(e.g. temperature, water chemistry, salinity, clarity). Therefore, Bio-efficacy for a given ship geographic location is defined by the following indicators:

- Minimum effect to change of seawater temperature
- Minimum effect to change of seawater salinity
- Minimum effect to change of seawater chemistry
- Minimum effect to change of seawater clarity

- **Percentage of ballast leg** means the voyage that a ship run through empty of cargo in a given year. Percentage of ballast leg can be indicated by the following indicators:

- *Percentage of sea time* with a ship loaded with cargo per year
- Percentage of sea time with empty ship's holds *(ballasted)* run per year
- Percentage of port time per year
- Percentage of time in dry dock (for maintenance) per year

- **Ship age** is the time in years between the ship inductions; in this study it is assumed that a ship is new when it is less than 8 years, middle age between 9-15 years, old ship more than 16 years onwards.

Appendix B

Survey criteria weighting questionnaire (Qualtrics web-site version).

Note the format is shortened by removing the repeated comparison scale for preferences which was presented before pairwise question in order to guide the decision maker.

Shipping Companies' Criteria Weighting Questionnaire

Dear Participant,

Today there are various ballast water treatment (BWT) technologies that claim to be effective in meeting the IMO Ballast Water Management (BWM Convention). It is worth noting that all these technologies vary in their approach to eliminate the harmful organisms, their environmental risks, safety, cost, processing time, capacity, etc.

This raises the question: Which of these ballast water treatment systems should a shipping company install into their ships?

This criteria weighting questionnaire is part of a PhD research study on the design of a decision tool to assist shipping companies select the most feasible ballast water treatment system their ships. The aim of this questionnaire is to prioritise (or evaluate) by weighting the identified criteria based on expert's judgments. It is obvious that the success of this investigation depends on the collaboration of experts by filling in this questionnaire. Your response by prioritising the identified criteria will be used to as input to the decision tool.

Your response will be of a great benefit to the validate the deigned decision tool as away for solving one of the current important challenges confronting shipping companies selecting the most suitable ballast water treatment system for their ships.
With your help, I will be able to complete my PhD study. Thank you for your kind cooperation.

Kind Regards
Hani H M H ALHababi, PhD Researcher
University of Strathclyde Glasgow, Department of Naval Architecture, Ocean and Marine Engineering (NAOME); Email: hani-h-m-h-alhababi@strath.ac.uk; Tel: (+44) 0141 548 4834

Before completing this questionnaire please note the following:

1- Please complete all the questions by giving your preferences (or judgments).

2- **An example** about the manner of answering the questions is displayed before starting the questionnaire. Generally, each question requires your inputs judgment in comparing two criteria to each other.

3- Please pay attention to the definitions displayed next page to assist you understand the meaning of the criteria in this questionnaire**.**

4- You are allowed **to go back** and check your added answers or definitions as you go along the questions.

<< >>

Survey Completion

0% 100%

Definitions

- **Cost** is monetary fees associated purchasing and installing a ballast water technology on-board a ship. The cost of a ballast water treatment system can be indicated by three aspects:
  - **Minimising capital cost** i.e. purchasing and installing fees;
  - **Minimising operating cost** e.g. cost associated with the technology power required;
  - **Minimising maintenance cost** i.e. associated with the routine & preventive actions for repairs, cleaning, replacing an item(s).
- **Safety** is the important role of being free of danger or risks. The safety of a ballast water treatment system for a given ship can be indicated by three aspects:
  - **Maximising environmental safety** i.e. risks to living environment when discharged;
  - **Maximising ship safety** e.g. corrosion to ballast tanks or hazardous to explosive space;
  - **Maximising crew safety e.g.** crew health.
- **Regulation** is the compliance with international maritime organisation (IMO) standards and specifically D-2 standards in addition to other states such as United States, Australia and Europe etc.
- **Ship compatibility** means the physical applicability of using a ballast water treatment on-board ship. Ship compatibility can be indicated by satisfying the following aspects:
  - **Satisfy limited space** is defined by the following indicators:
    - Compact as one unit, that means can be fitted in confined space;
    - Can be installed in a hazardous space
    - Minimum requirement to additional equipment e.g. pump, tanks, piping, storage etc.
  - **Satisfying process time** is defined by the following indicators:
    - Satisfy ship operating mode, whether follow a liner or tramp service, allows capturing the limited time for a ballast water technology to process in a given ship.
    - Satisfy ship voyage length, this depends on the ship speed as well to define the time required for a ballast water treatment system to process in a given time.
  - **Maximum ability to treat ship ballast water capacity** is defined by the following indicators:
    - Ship size can define the approximate ballast water system capacity.
  - **Minimum interruption to ship emergency system.**
  - **Maximum ease of operation.**
  - **Minimum ship operating cost** is defined by the following indicators:
    - Minimum requirement for extra expertise.
    - Minimum requirement for crew training.
    - Minimum fuel consumption
    - Maximum ease for maintenance

- **Bio-efficacy** is associated with the ability of a ballast water treatment to effectively reduce or/and eliminate harmful organisms from ballast water. However, studies found that bio-efficacy can be altered (or influenced) under the change indicators (e.g. temperature, water chemistry, salinity, clarity). Therefore, Bio-efficacy for a given ship geographic location is defined by the following indicators:
  - Minimum effect to change of seawater temperature
  - Minimum effect to change of seawater salinity
  - Minimum effect to change of seawater chemistry
  - Minimum effect to change of seawater clarity

Example for answering the questions

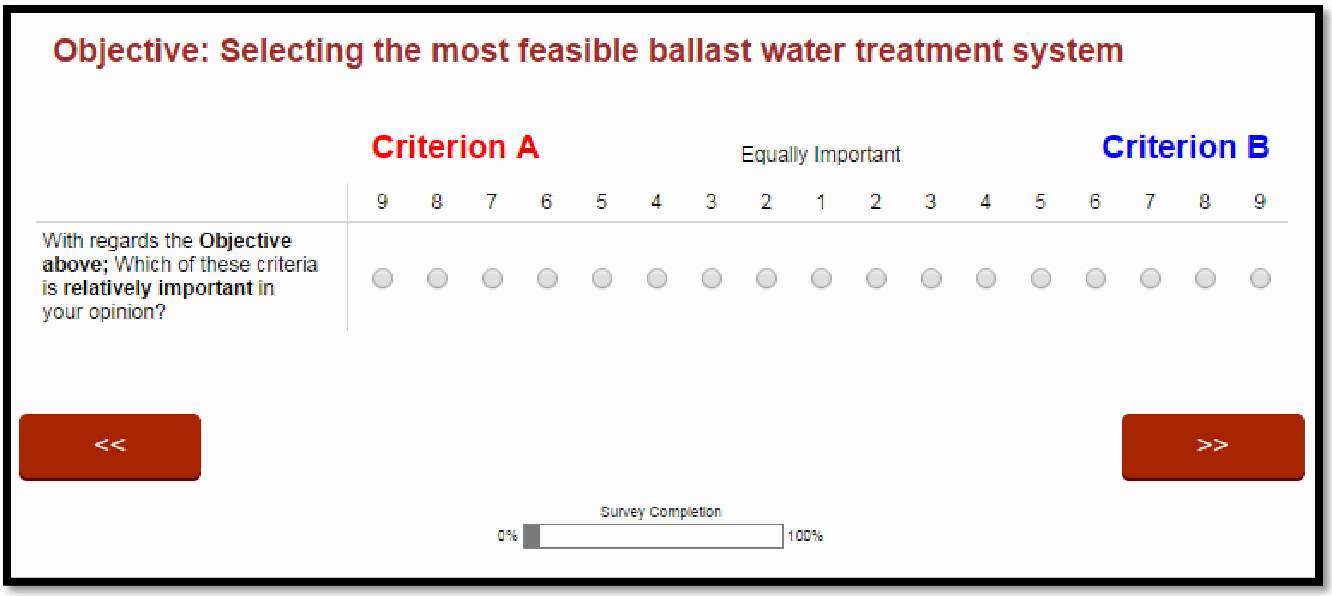
Importance	Definition	Explanation
1	**Equal Importance**	Two activities contributed equally to objective
2	**Weak or slight**	
3	**Moderate importance**	Experience and judgement strongly favour one activity over the other
4	**Moderate plus**	
5	**Strong Importance**	Experience and judegement strongly favour one activity over another
6	**Strong plus**	
7	**Very strong importance**	One activity is very strongly favoured over the other; its dominance demonstrated in practice
8	**Very, very strong**	
9	**Extreme Importance**	The evidence of favouring one activity over another is the highest possible order of affirmation

Table: Comparison scale for preferences

Use the table above as a guide to help you judge how much one criterion is more important to another one by selecting the number 1-9 in the specified place.

For example if A and B are the given elements:

- If **A** and **B** are **equally important** in your opinion, insert **1**
- If **A** is **slightly or weakly more important** than **B** in your opinion ,insert **2**
- If **A** is **moderate important** than **B**, insert **3**
- If **A** is **moderate plus important** than **B**, insert **4**
- If **A** is **strongly more important** than **B**, insert **5**
- If **A** is **strong plus more important** than **B**, insert **6**
- If **A** is **demonstrably or very strongly more important** than **B**, insert **7**
- If **A** is **very very strong more important** than **B**, insert **8**
- If **A** is **extremely more important** than **B**, insert **9**
- if **A & A** or **B & B** are compared with itself, insert **1**



Example for answering the questions

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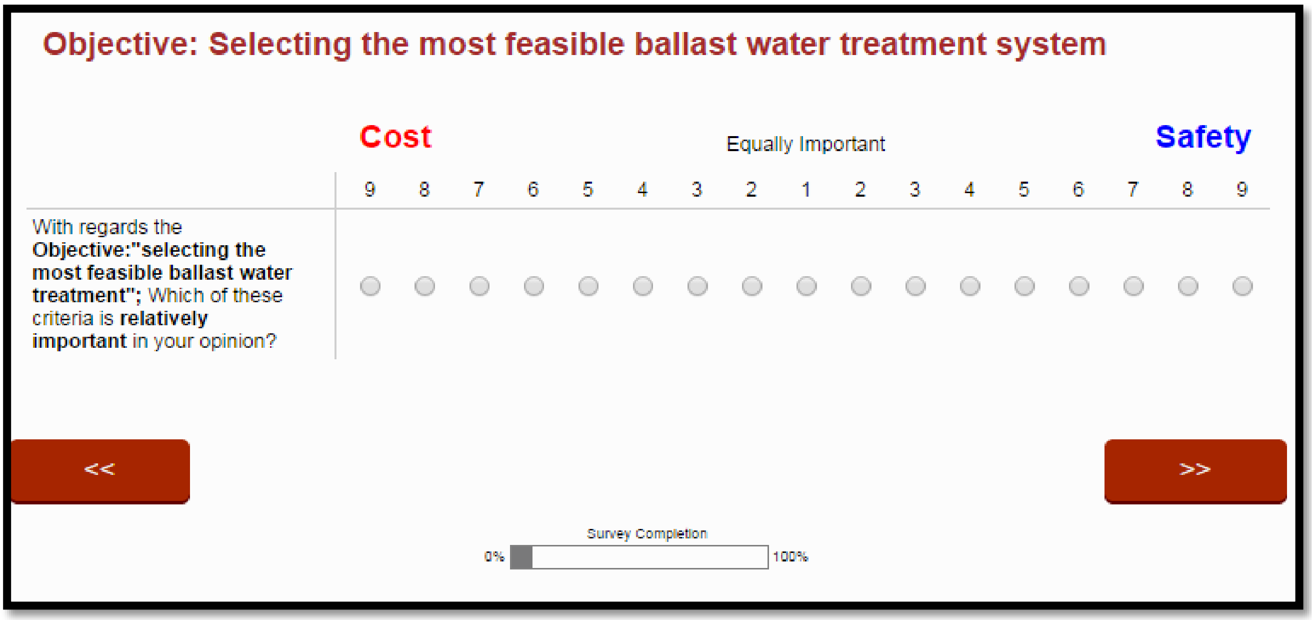
- If **A** is **strong plus more important** than **B**, insert **6**
- If **A** is **demonstrably or very strongly more important** than **B**, insert **7**
- If **A** is **very very strong more important** than **B**, insert **8**
- If **A** is **extremely more important** than **B**, insert **9**
- if **A & A** or **B & B** are compared with itself, insert **1**


Objective: Selecting the most feasible ballast water treatment system
Cost
Equally Important
Safety
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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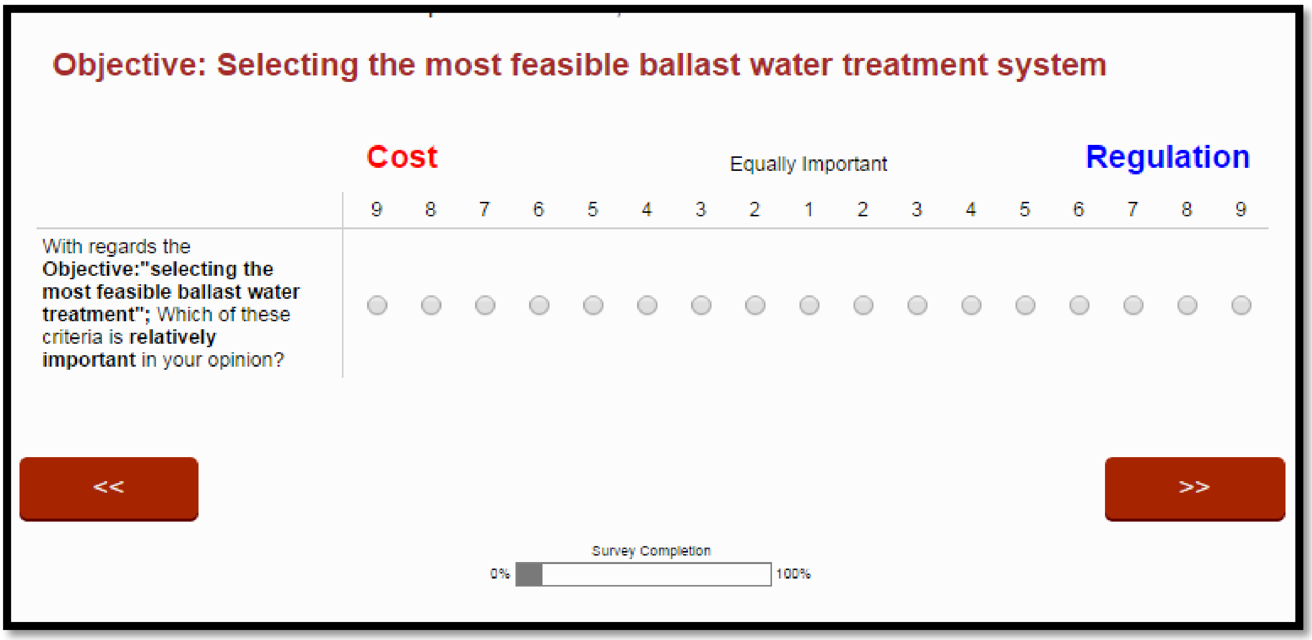
Objective: Selecting the most feasible ballast water treatment system
Cost
Equally Important
Regulation
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With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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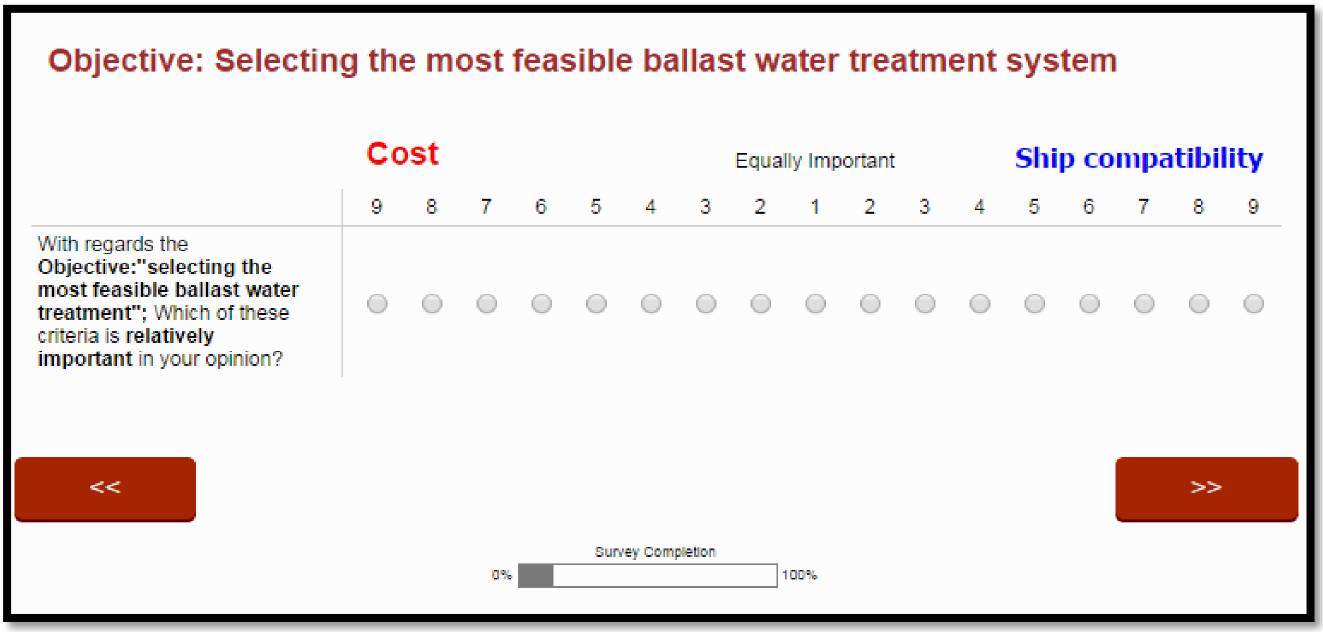
Objective: Selecting the most feasible ballast water treatment system
Cost
Equally Important
Ship compatibility
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the **Objective:"selecting the most feasible ballast water treatment";** Which of these criteria is **relatively important** in your opinion?
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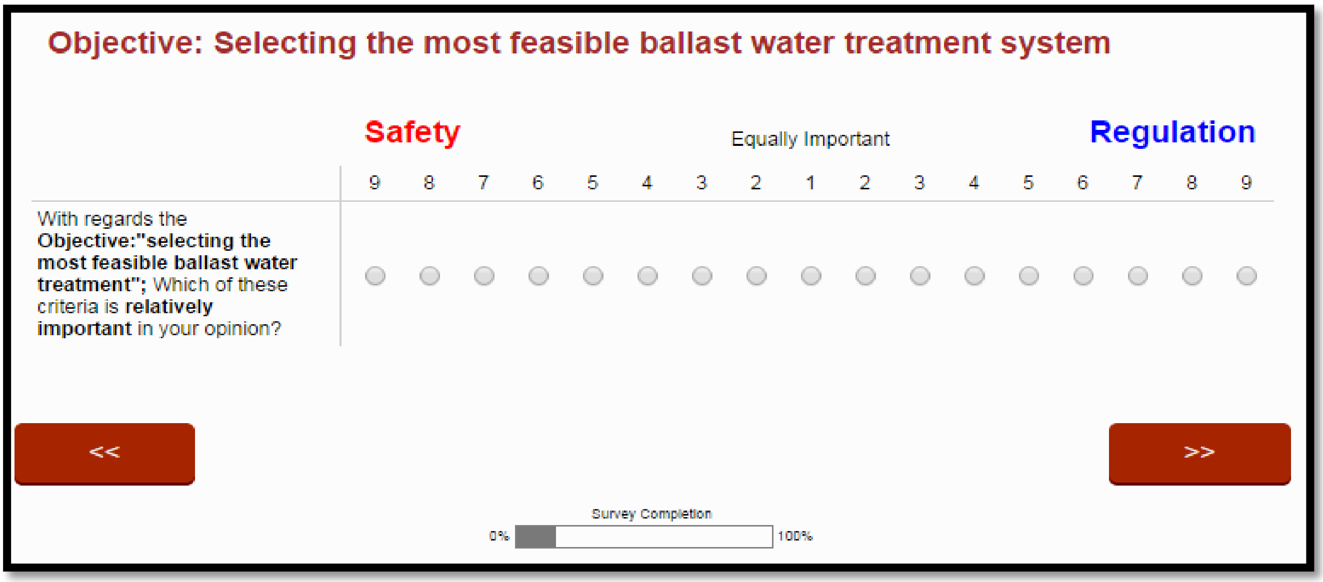
Objective: Selecting the most feasible ballast water treatment system
Safety
Equally Important
Regulation
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the **Objective:"selecting the most feasible ballast water treatment";** Which of these criteria is **relatively important** in your opinion?
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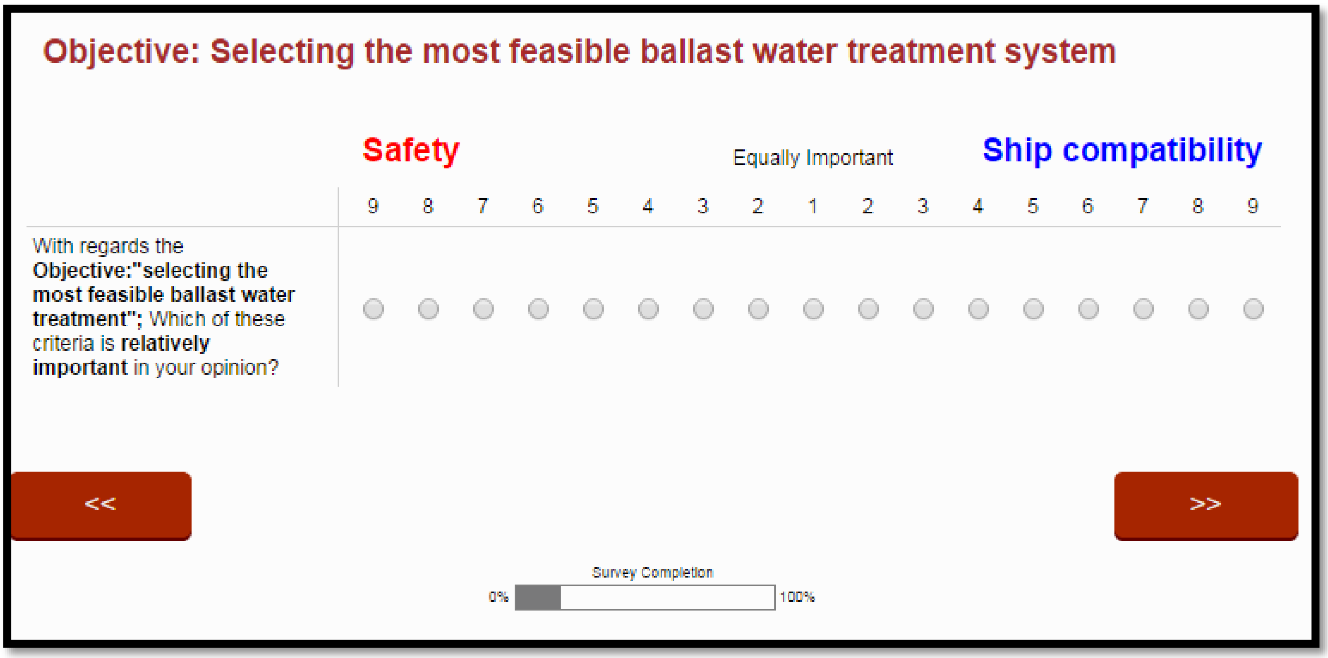
Objective: Selecting the most feasible ballast water treatment system
Safety
Equally Important
Ship compatibility
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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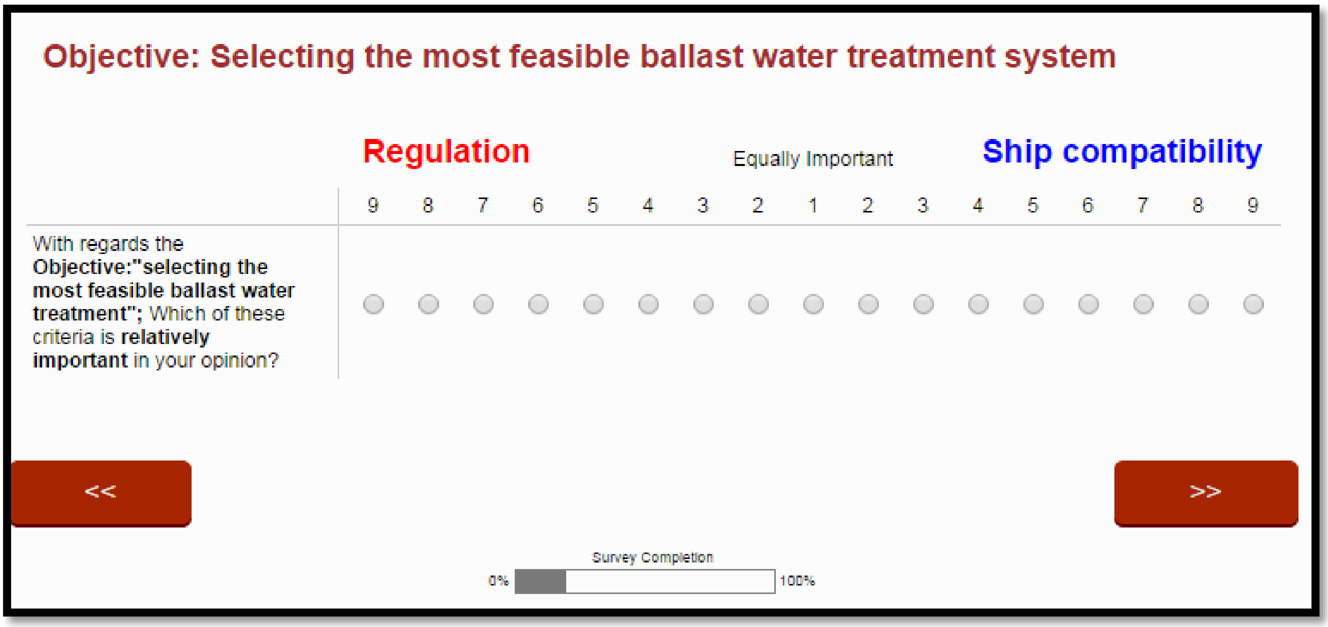
Objective: Selecting the most feasible ballast water treatment system
Regulation
Equally Important
Ship compatibility
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With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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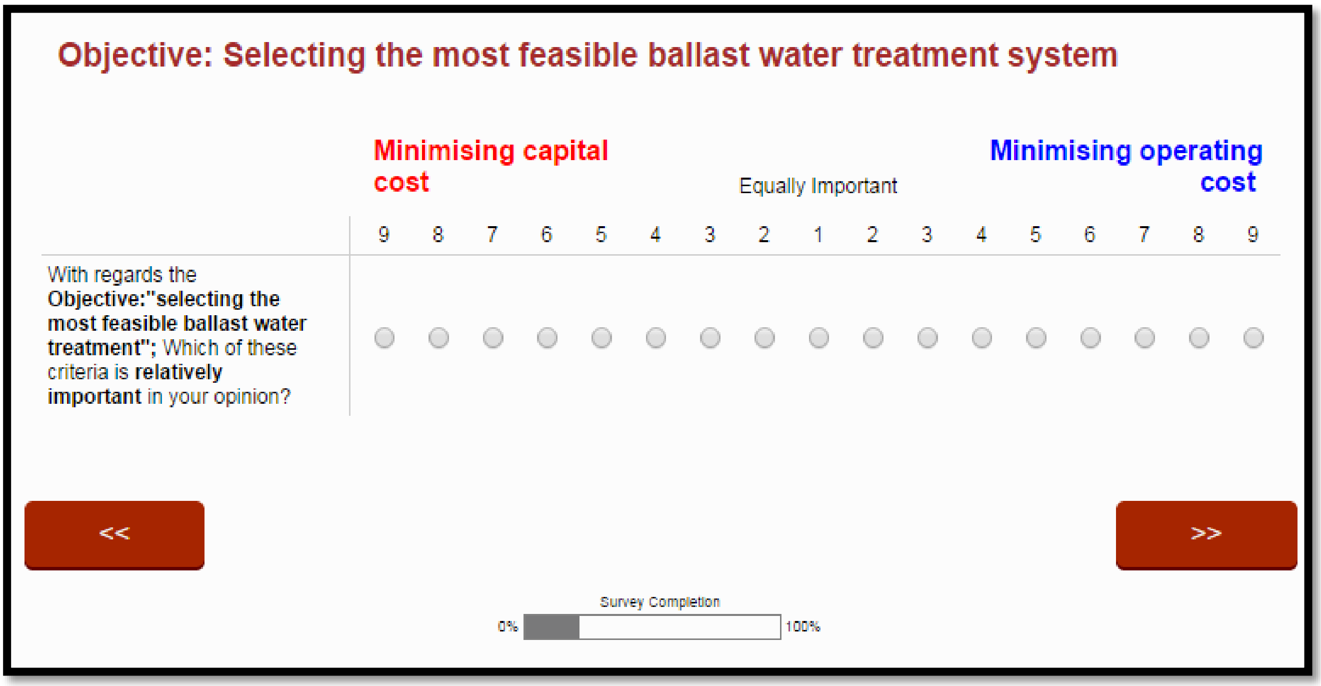
Objective: Selecting the most feasible ballast water treatment system
Minimising capital cost
Equally Important
Minimising operating cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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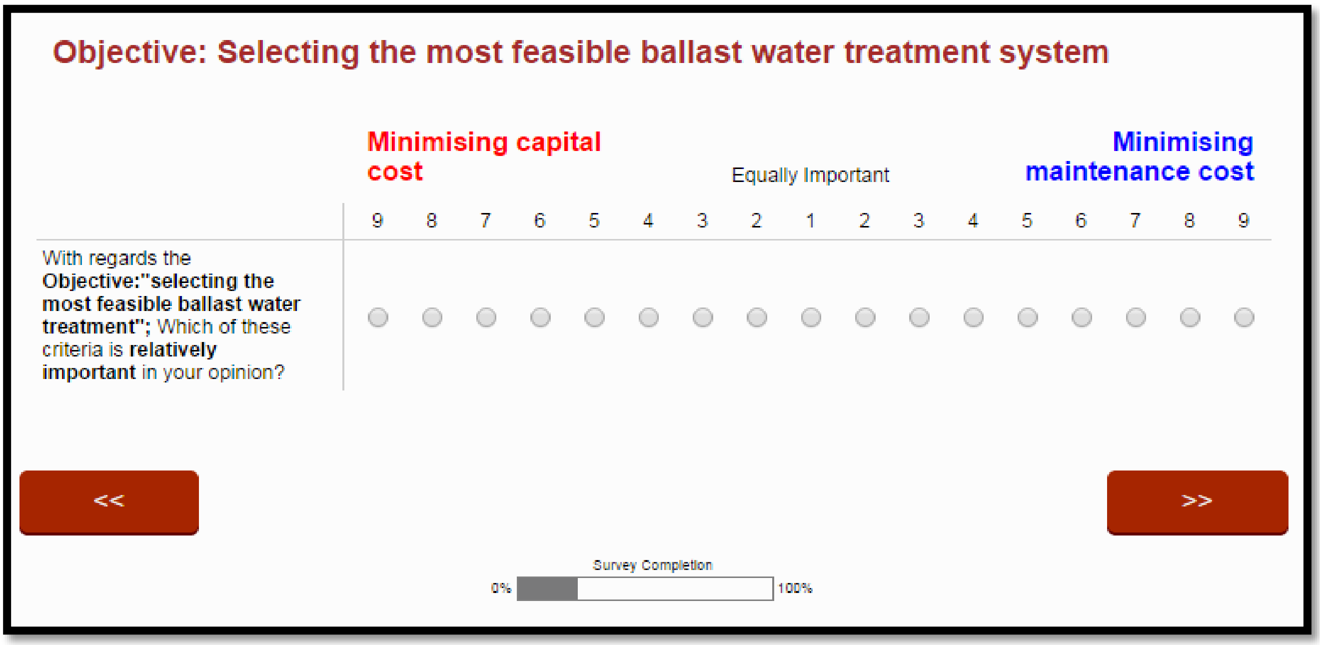
Objective: Selecting the most feasible ballast water treatment system
Minimising capital cost
Equally Important
Minimising maintenance cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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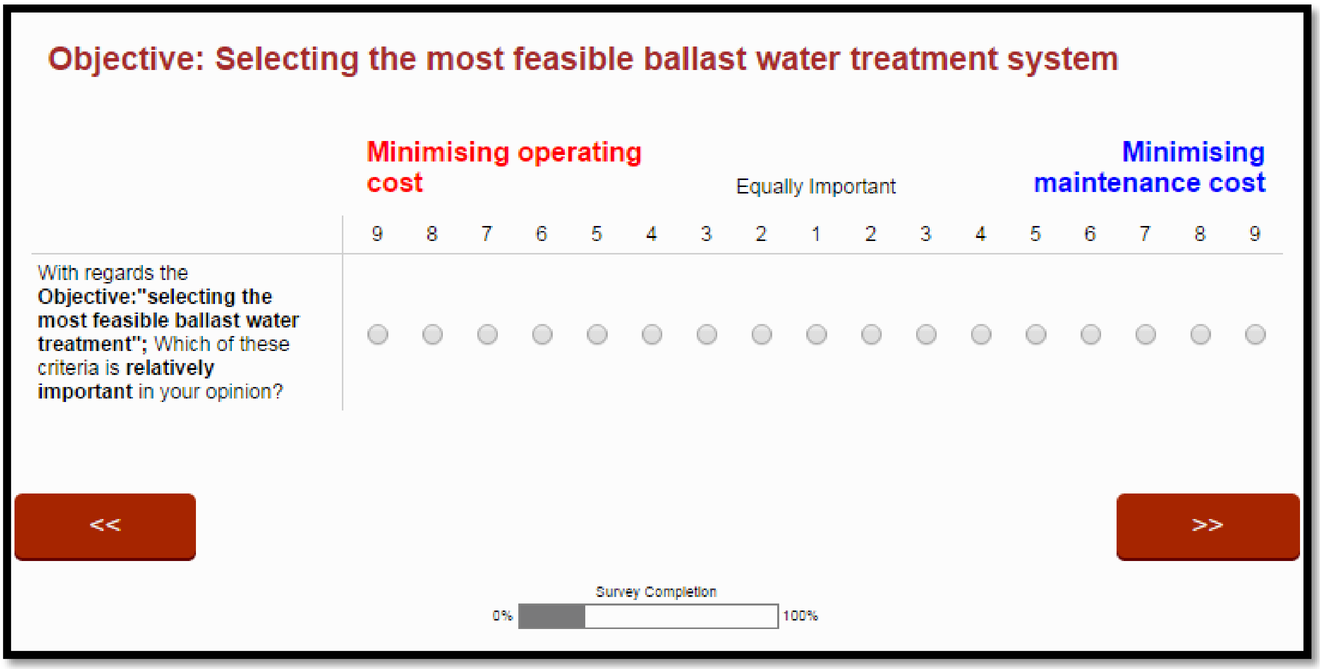
Objective: Selecting the most feasible ballast water treatment system
Minimising operating cost
Equally Important
Minimising maintenance cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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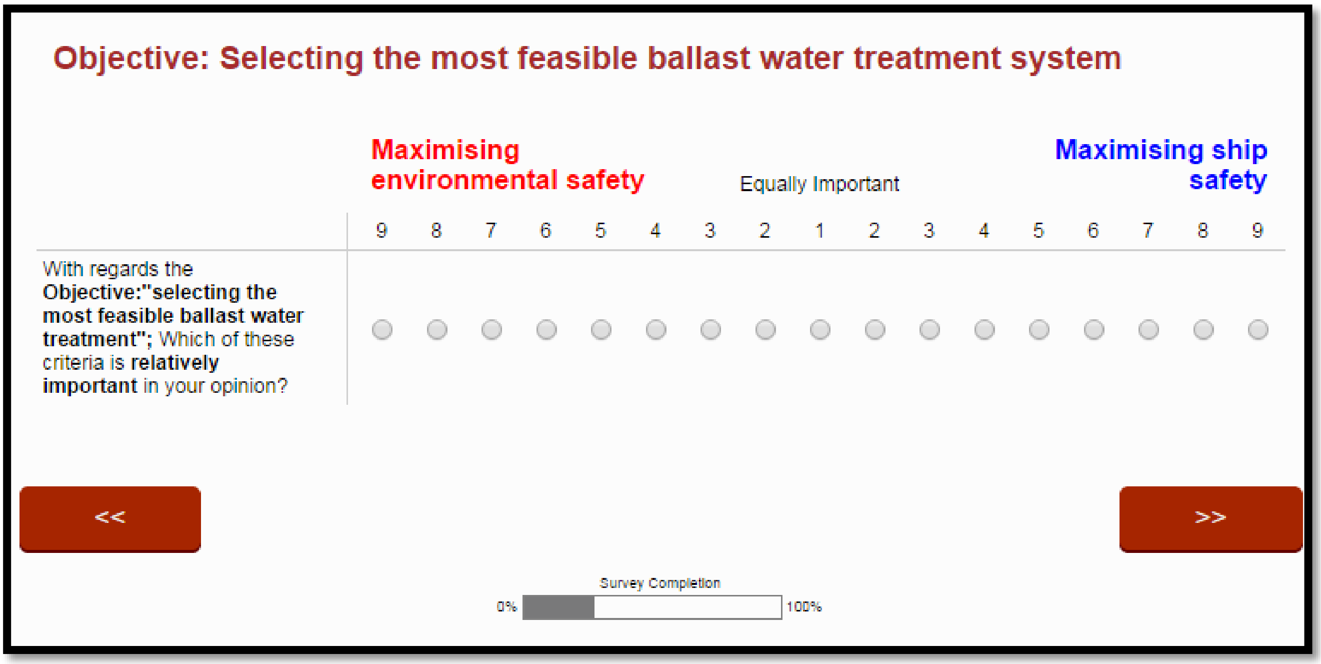
Objective: Selecting the most feasible ballast water treatment system
Maximising environmental safety
Equally Important
Maximising ship safety
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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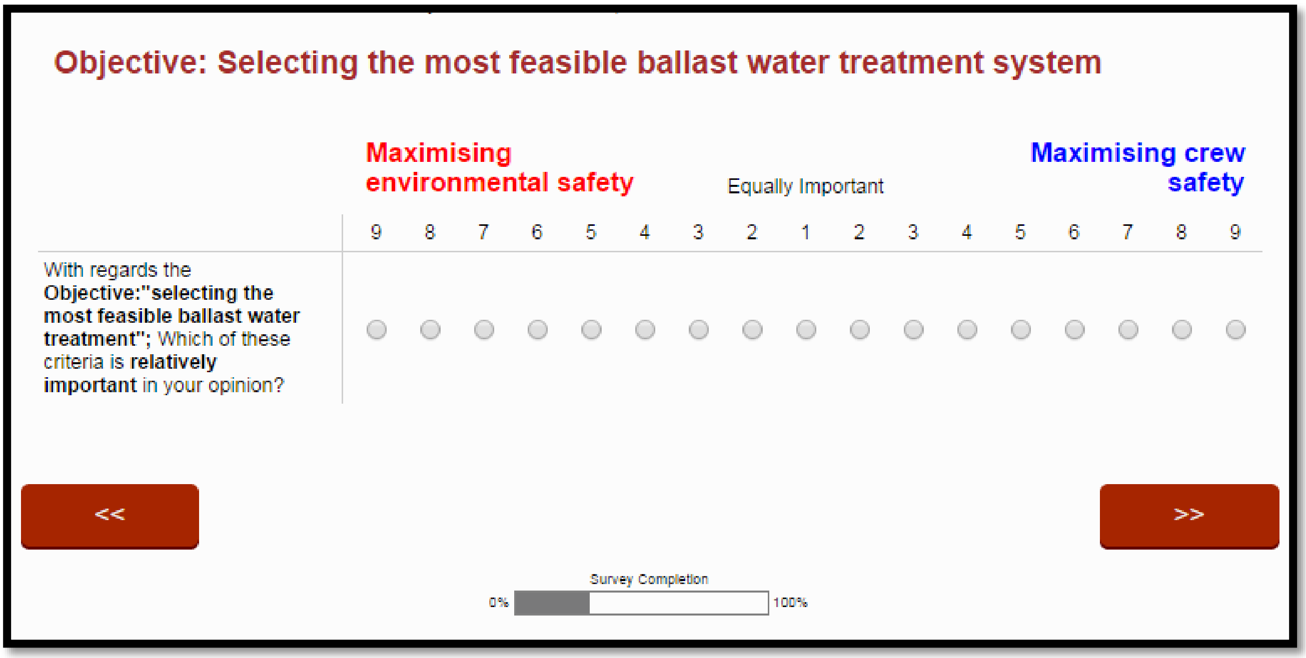
Objective: Selecting the most feasible ballast water treatment system
Maximising environmental safety
Equally Important
Maximising crew safety
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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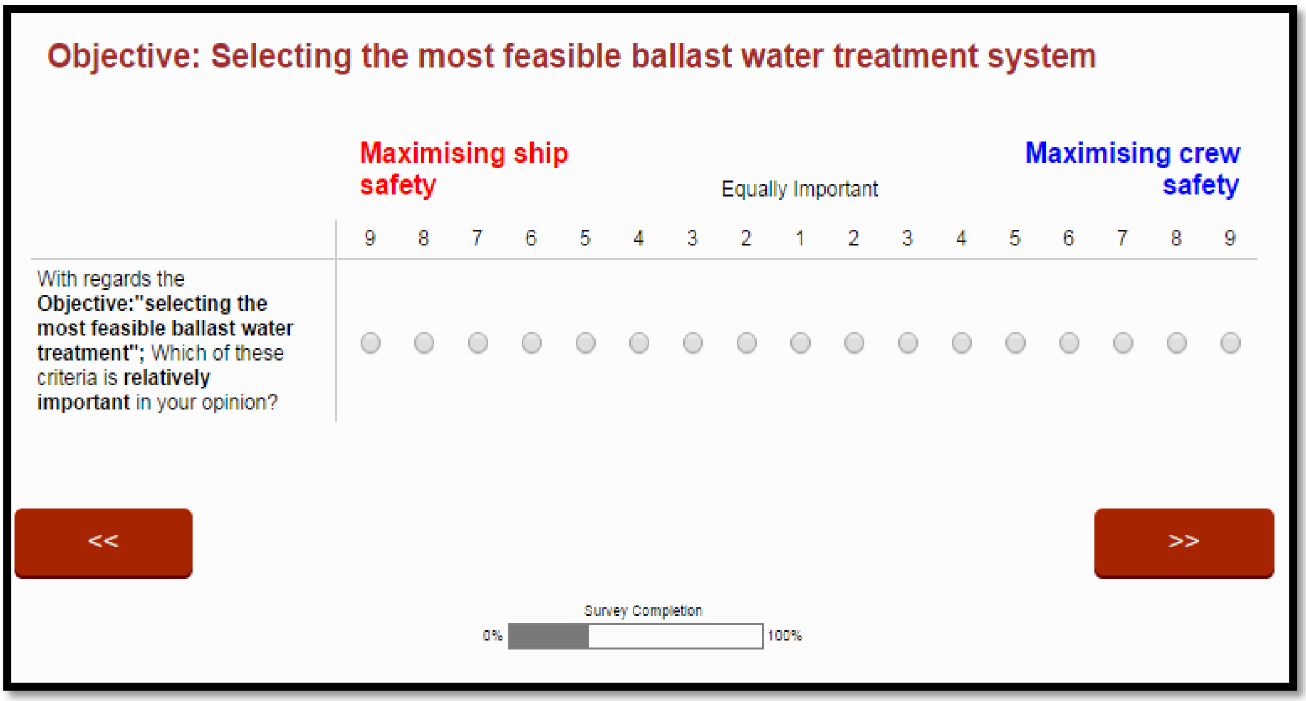
Objective: Selecting the most feasible ballast water treatment system
Maximising ship safety
Equally Important
Maximising crew safety
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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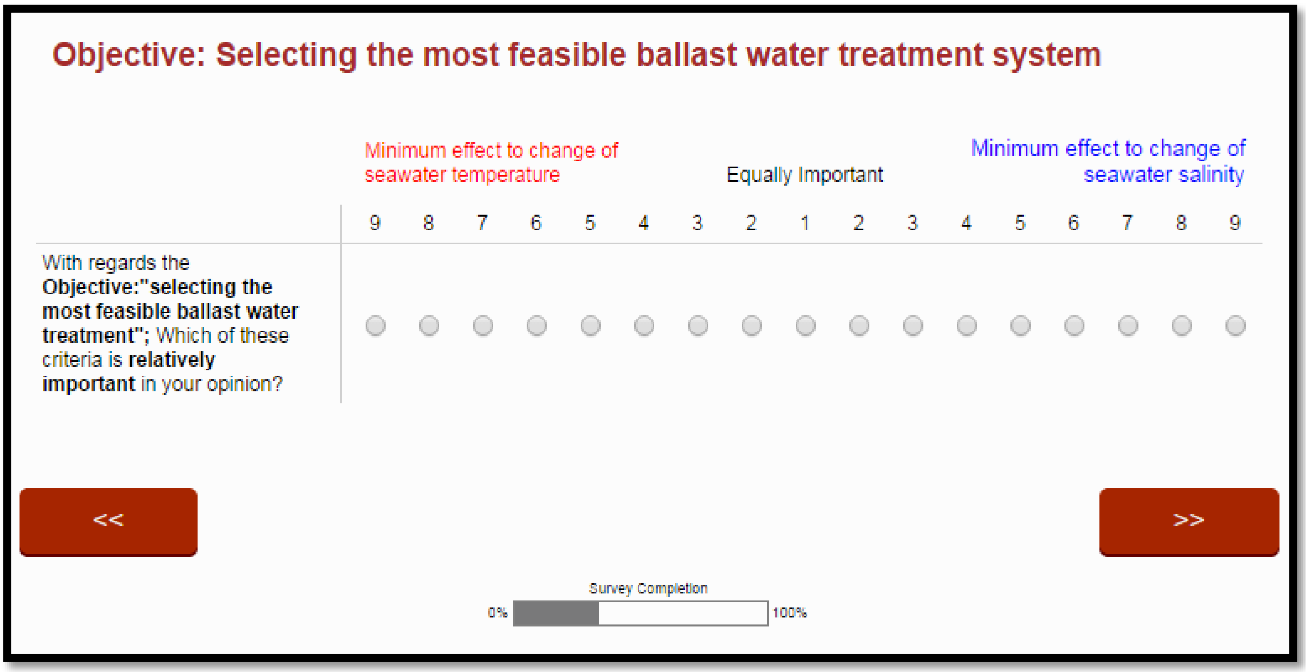
Objective: Selecting the most feasible ballast water treatment system
Minimum effect to change of seawater temperature
Equally Important
Minimum effect to change of seawater salinity
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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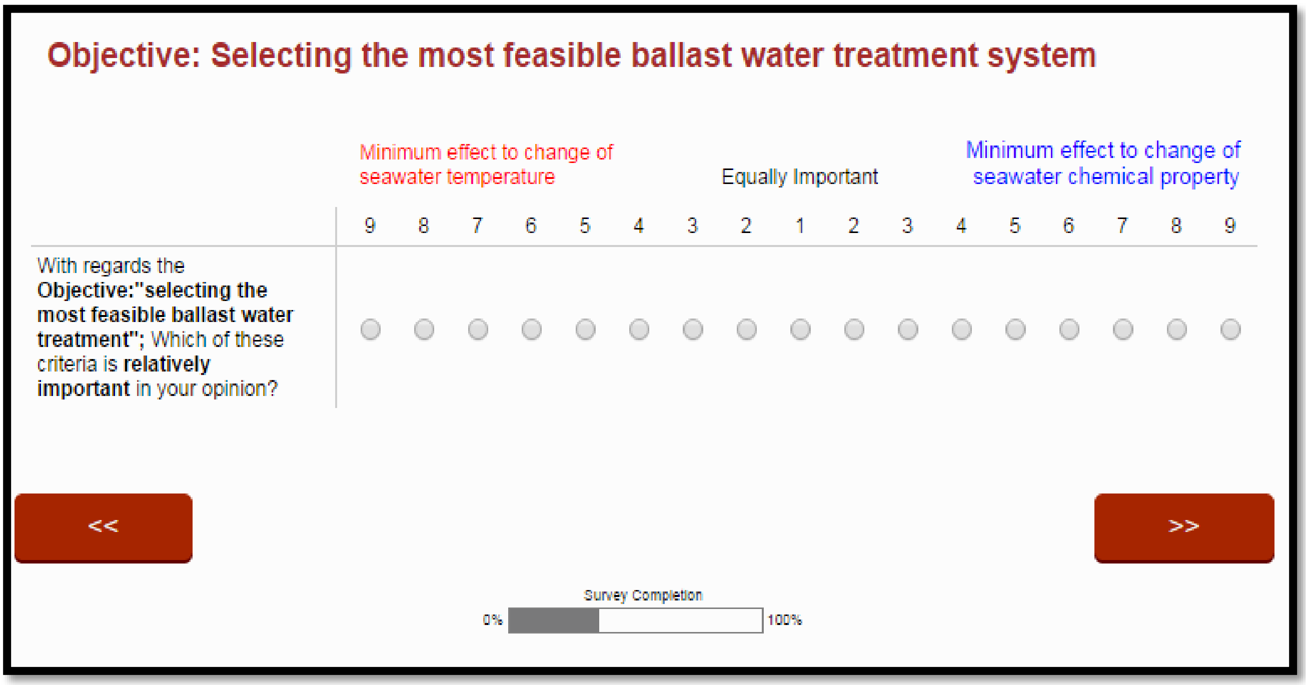
Objective: Selecting the most feasible ballast water treatment system
Minimum effect to change of seawater temperature
Equally Important
Minimum effect to change of seawater chemical property
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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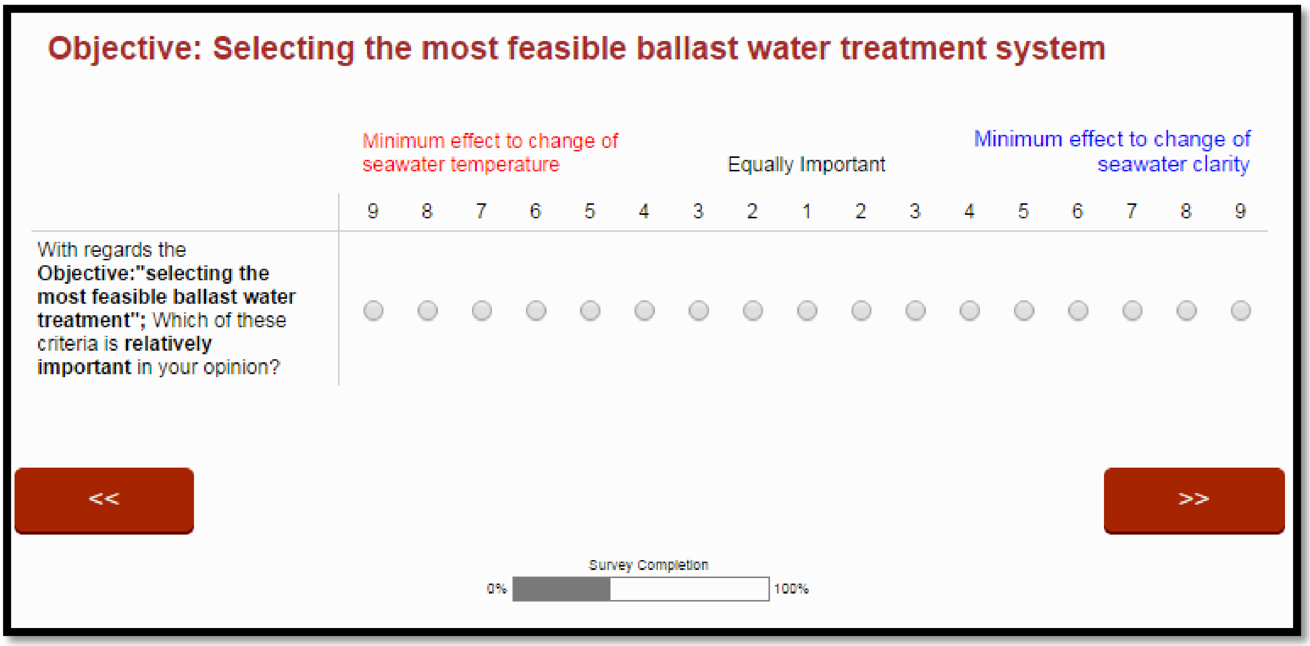
Objective: Selecting the most feasible ballast water treatment system
Minimum effect to change of seawater temperature
Equally Important
Minimum effect to change of seawater clarity
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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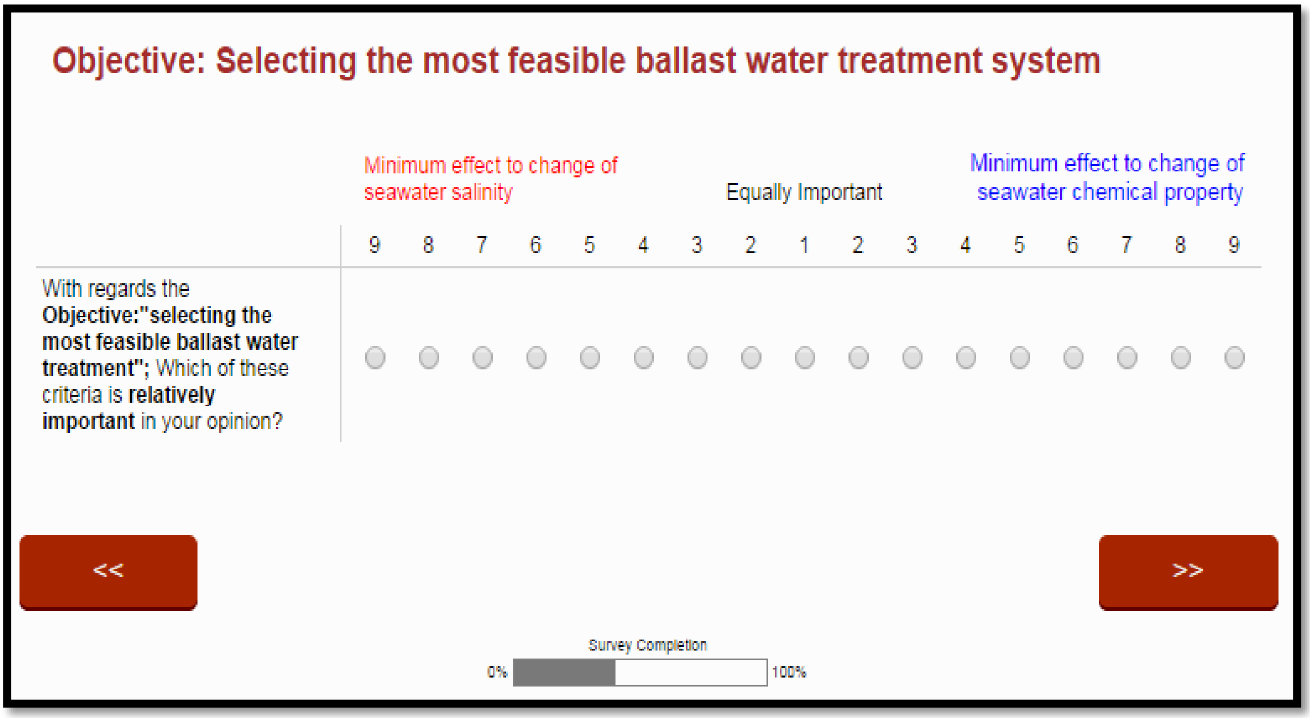
Objective: Selecting the most feasible ballast water treatment system
Minimum effect to change of seawater salinity
Equally Important
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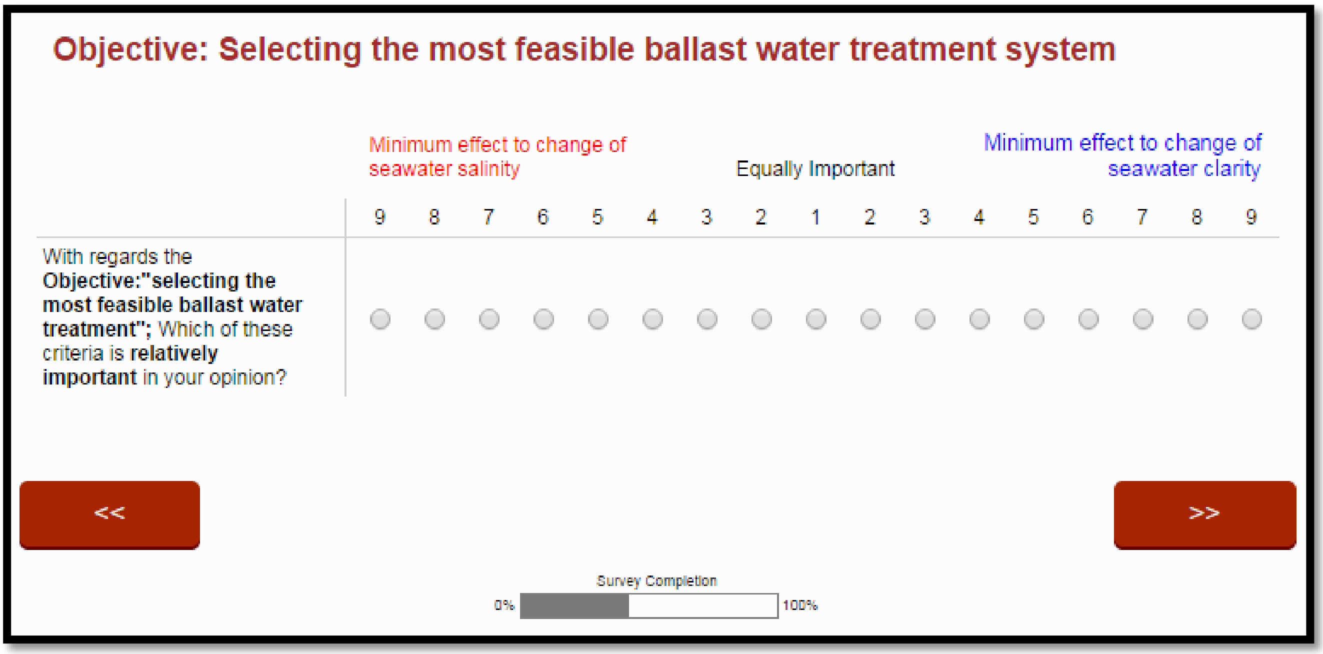
Objective: Selecting the most feasible ballast water treatment system
Minimum effect to change of seawater salinity
Equally Important
Minimum effect to change of seawater clarity
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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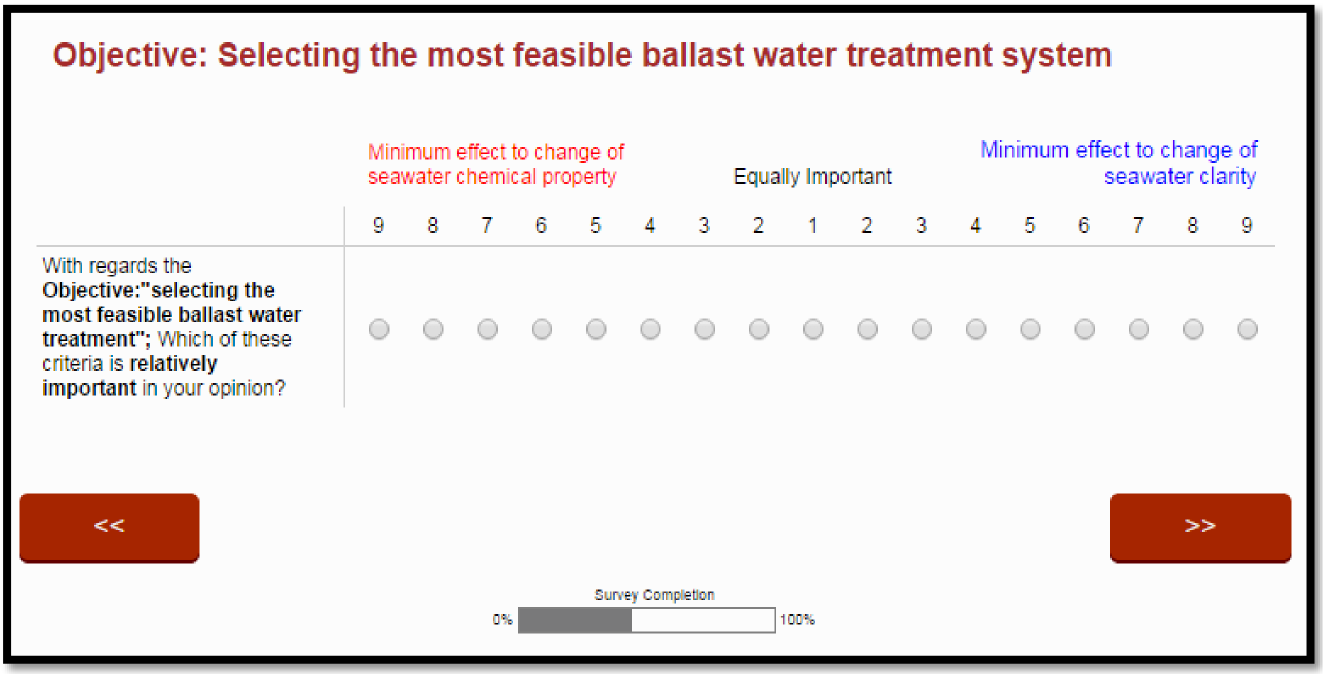
Objective: Selecting the most feasible ballast water treatment system
Minimum effect to change of seawater chemical property
Equally Important
Minimum effect to change of seawater clarity
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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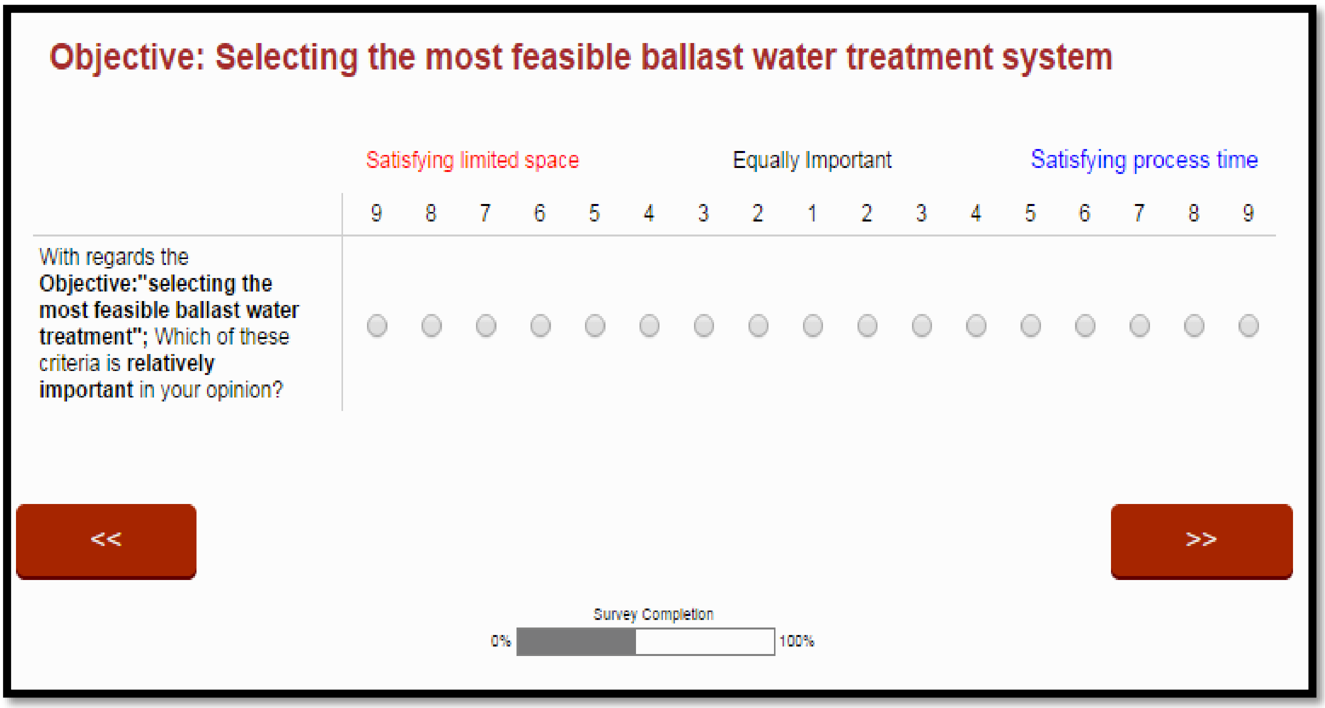
Objective: Selecting the most feasible ballast water treatment system
Satisfying limited space
Equally Important
Satisfying process time
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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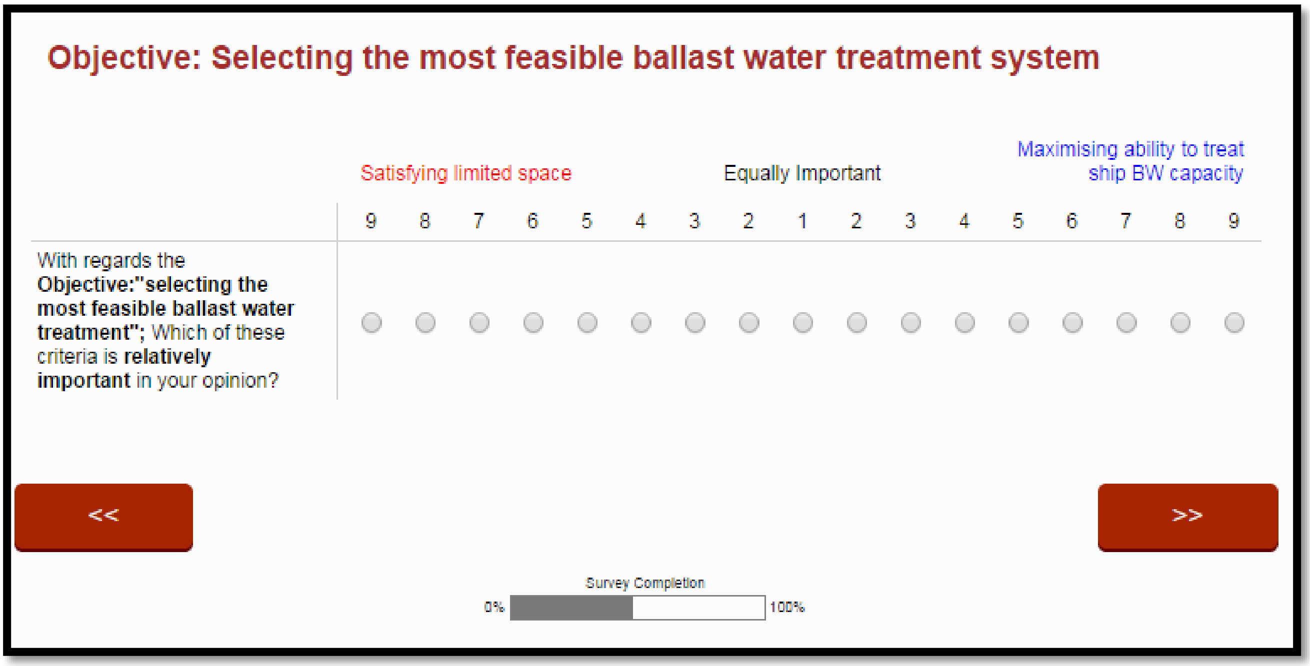
Objective: Selecting the most feasible ballast water treatment system
Satisfying limited space
Equally Important
Maximising ability to treat ship BW capacity
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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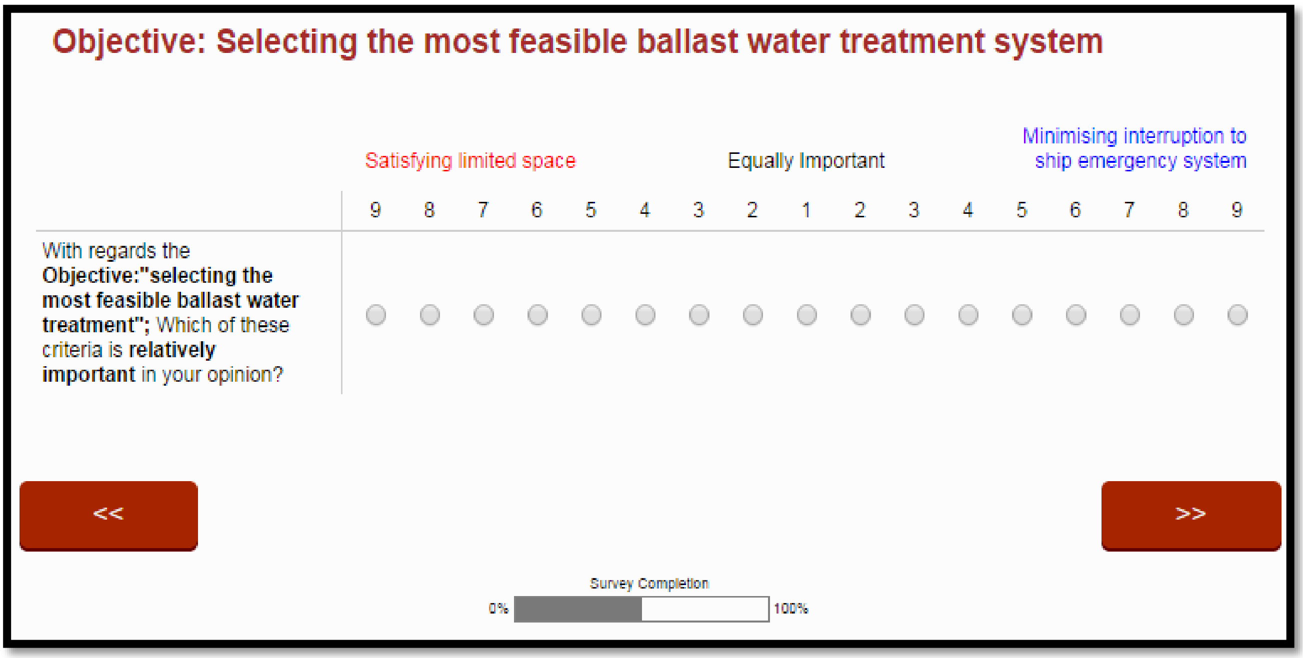

Objective: Selecting the most feasible ballast water treatment system

	Satisfying limited space								Equally Important								Minimising interruption to ship emergency system
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
With regards the **Objective:"selecting the most feasible ballast water treatment"; ** Which of these criteria is **relatively important** in your opinion?																	

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Survey Completion

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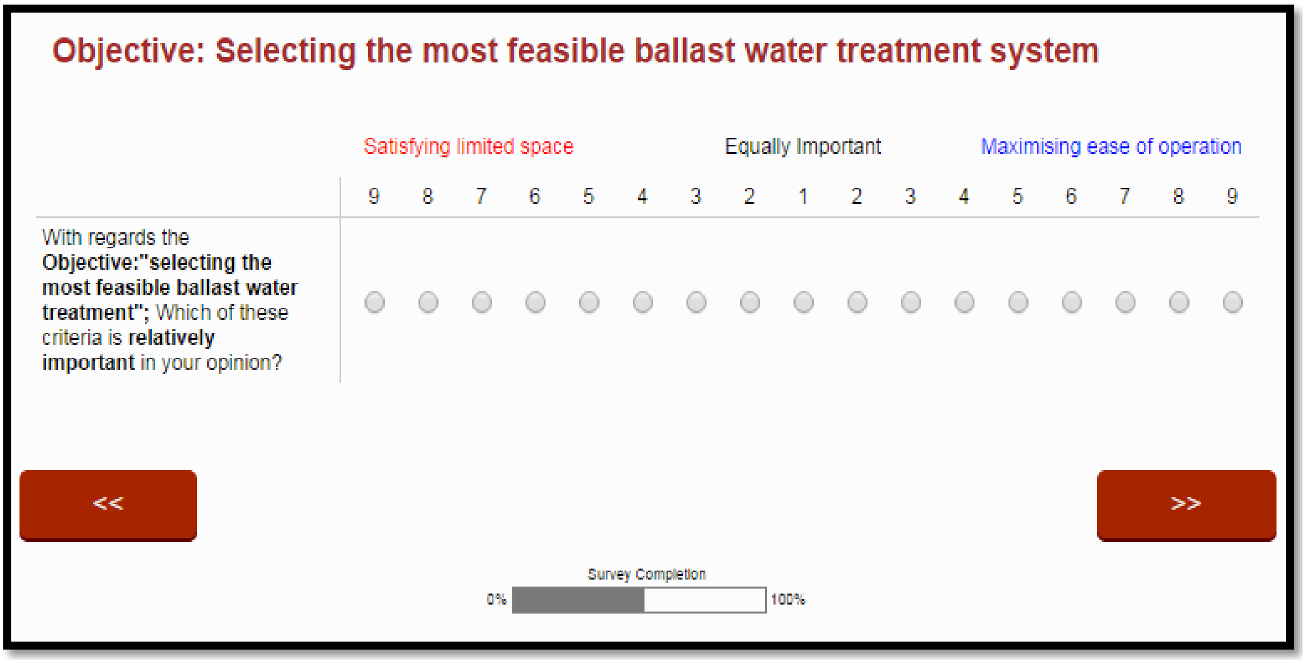

Objective: Selecting the most feasible ballast water treatment system

	Satisfying limited space								Equally Important								Maximising ease of operation
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
With regards the **Objective:"selecting the most feasible ballast water treatment"; ** Which of these criteria is **relatively important** in your opinion?																	

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Survey Completion

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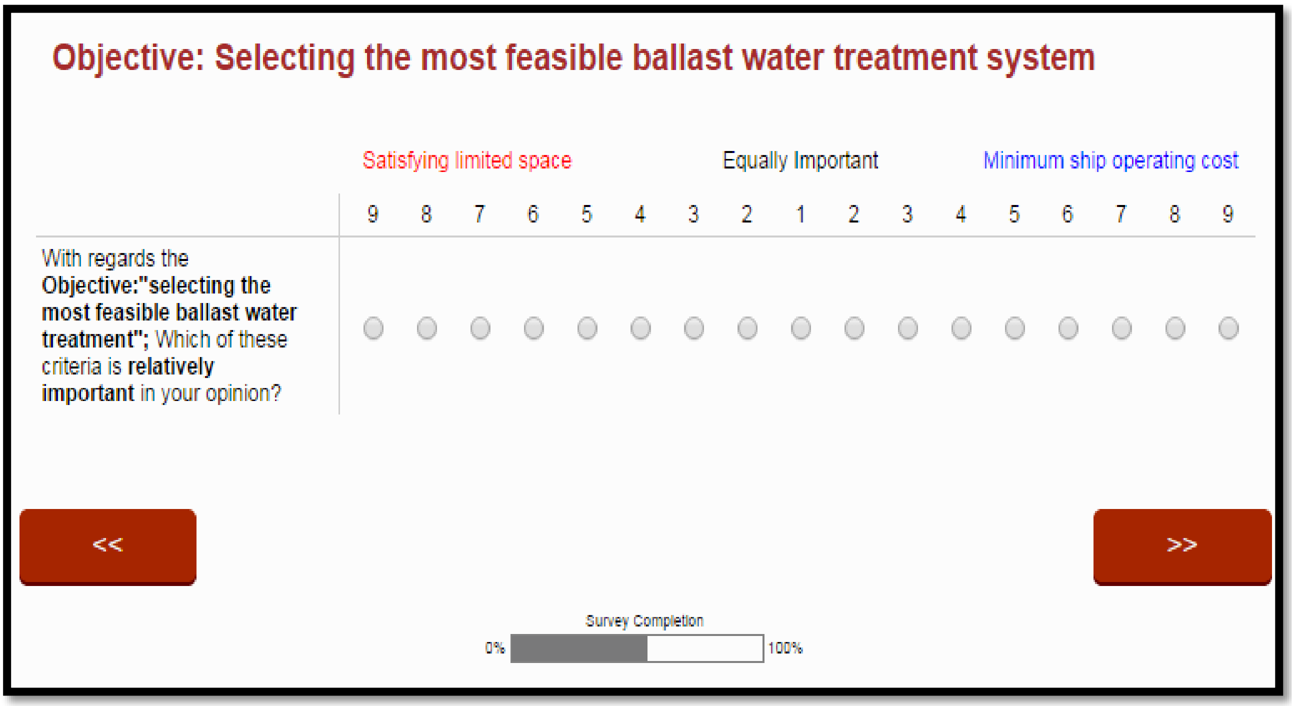
Objective: Selecting the most feasible ballast water treatment system
Satisfying limited space
Equally Important
Minimum ship operating cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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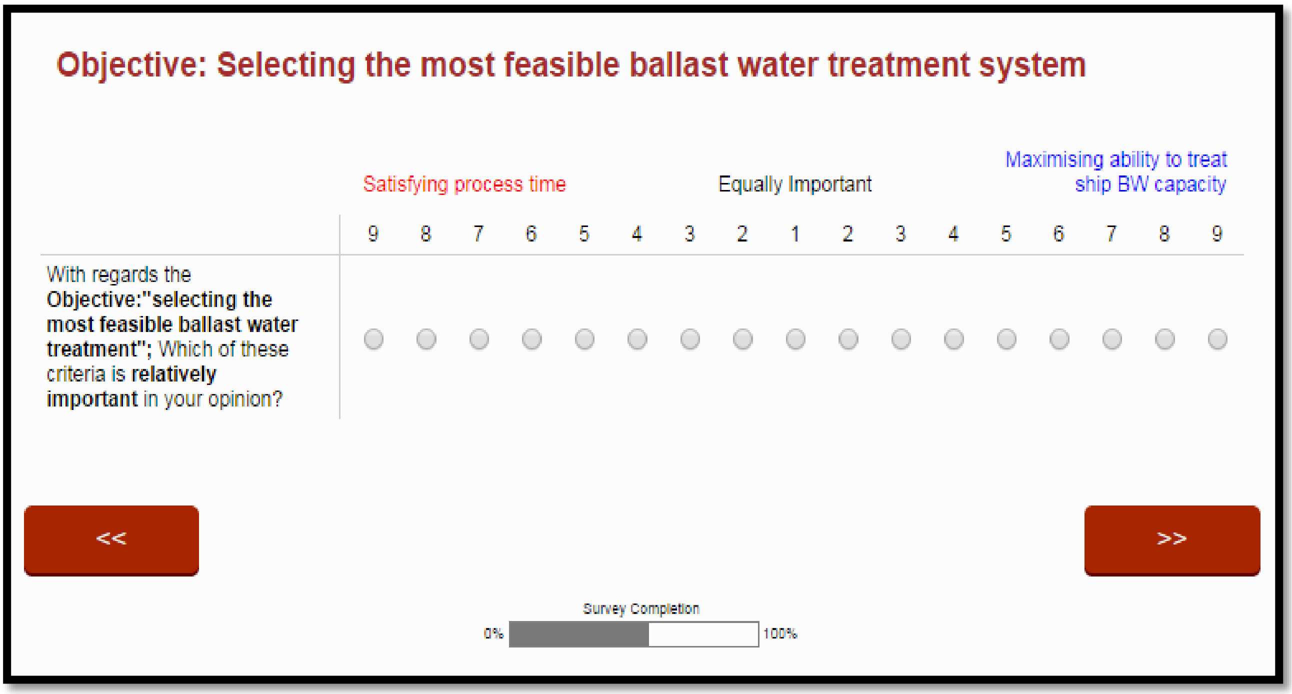
Objective: Selecting the most feasible ballast water treatment system
Satisfying process time
Equally Important
Maximising ability to treat ship BW capacity
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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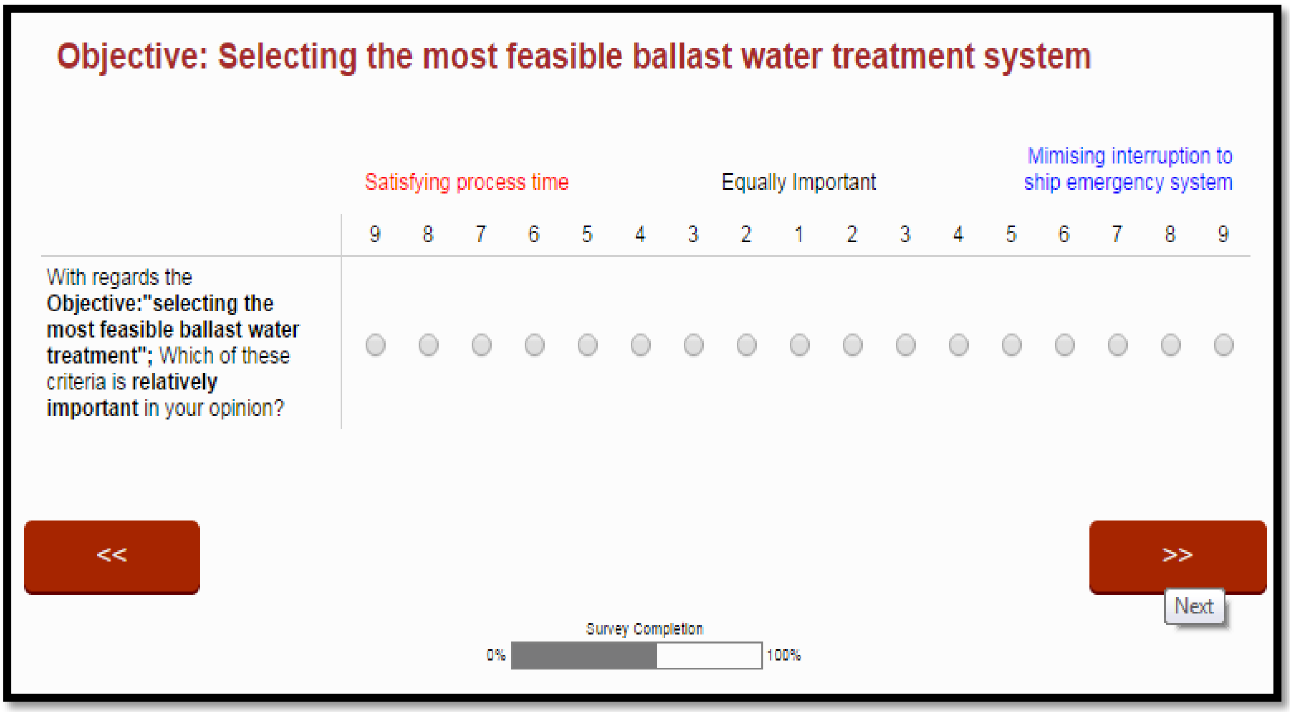
Objective: Selecting the most feasible ballast water treatment system
Satisfying process time
Equally Important
Mimising interruption to ship emergency system
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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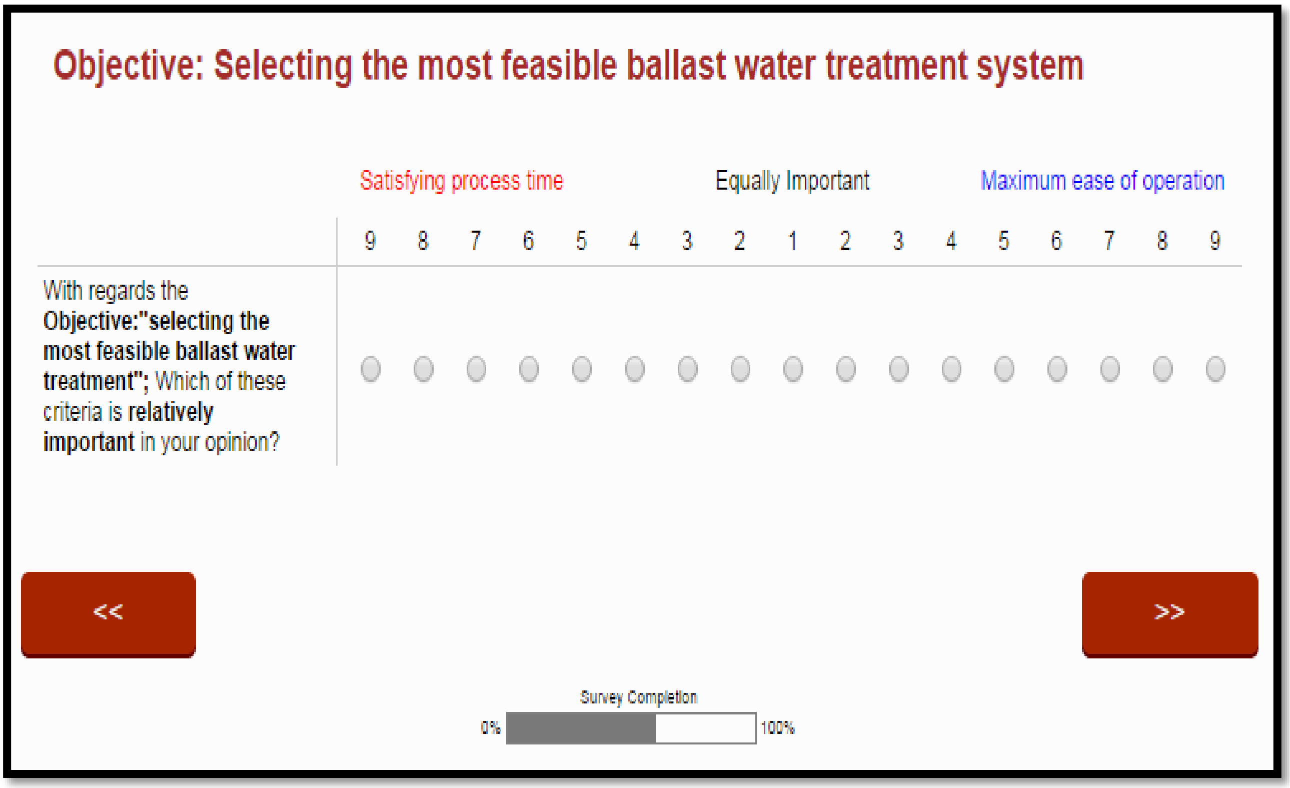
Objective: Selecting the most feasible ballast water treatment system
Satisfying process time
Equally Important
Maximum ease of operation
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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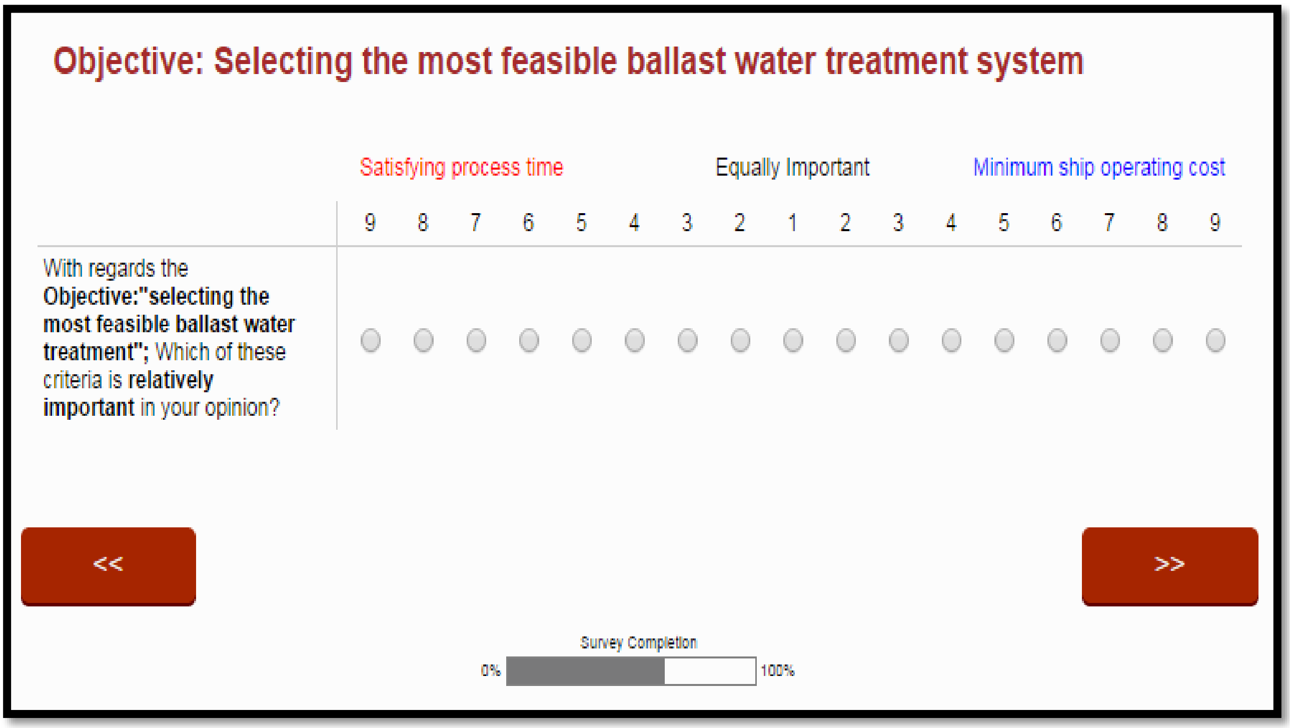
Objective: Selecting the most feasible ballast water treatment system
Satisfying process time
Equally Important
Minimum ship operating cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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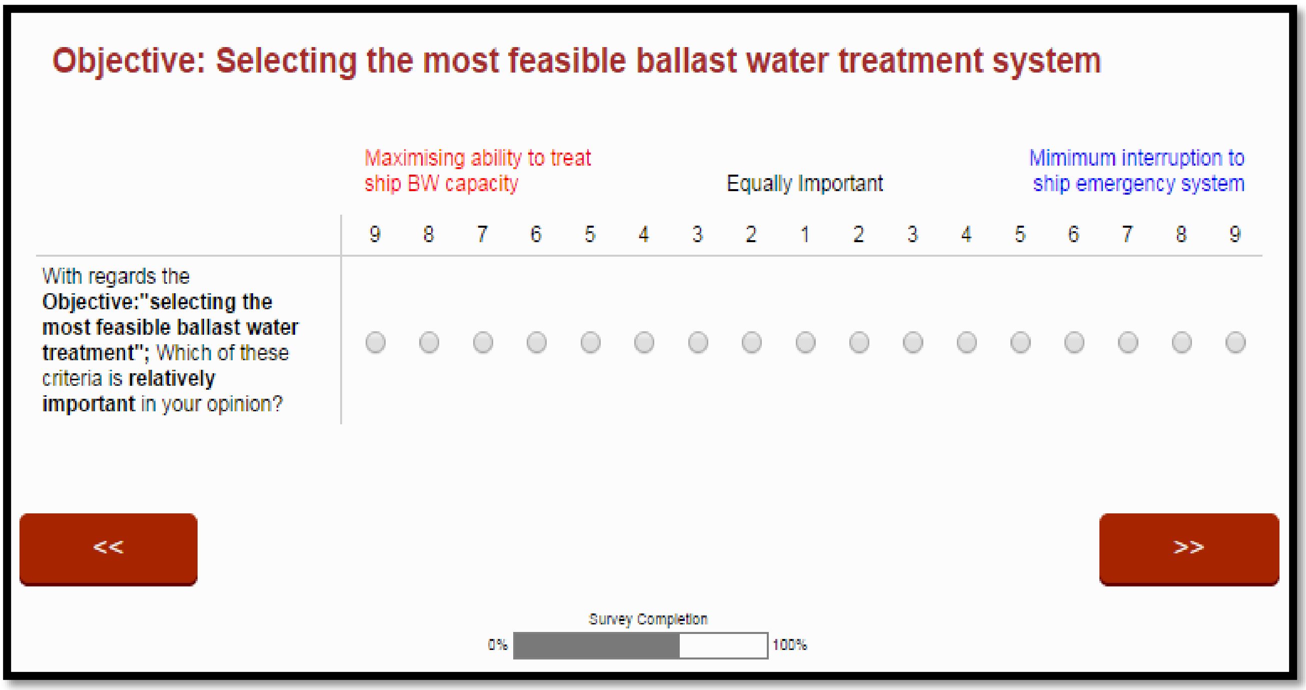
Objective: Selecting the most feasible ballast water treatment system
Maximising ability to treat ship BW capacity
Equally Important
Mimimum interruption to ship emergency system
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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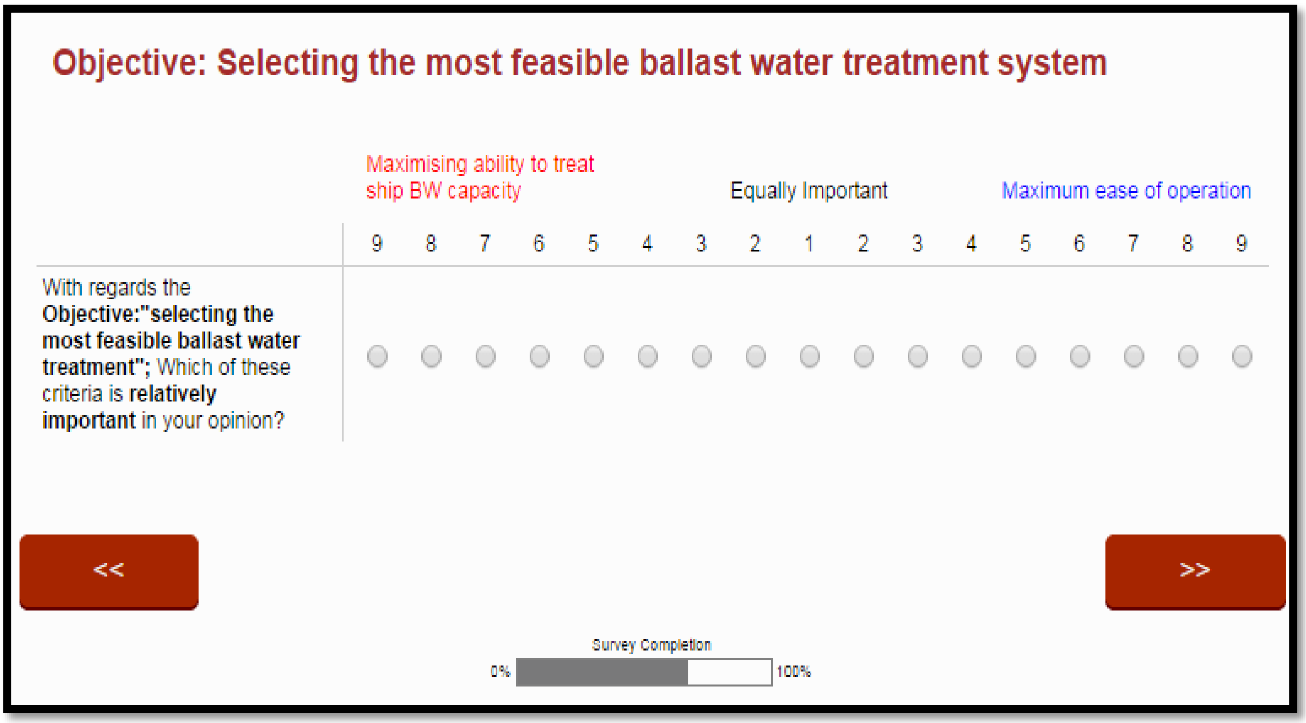
Objective: Selecting the most feasible ballast water treatment system
Maximising ability to treat ship BW capacity
Equally Important
Maximum ease of operation
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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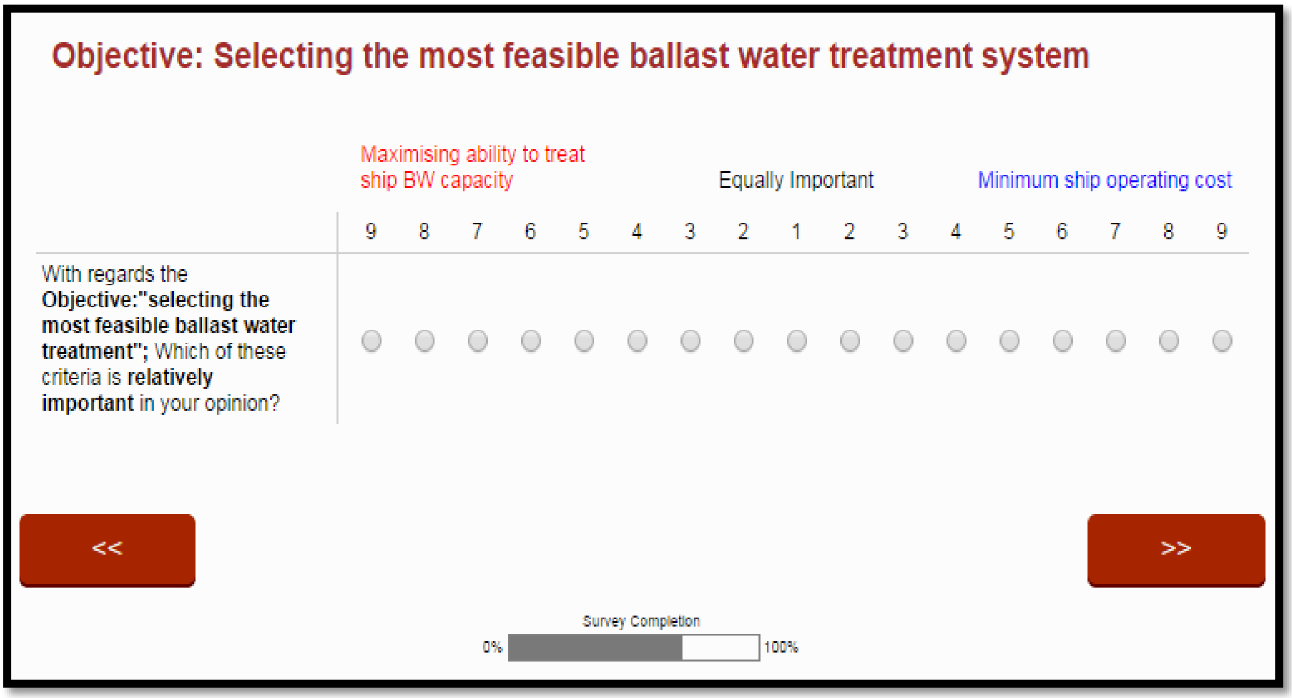
Objective: Selecting the most feasible ballast water treatment system
Maximising ability to treat ship BW capacity
Equally Important
Minimum ship operating cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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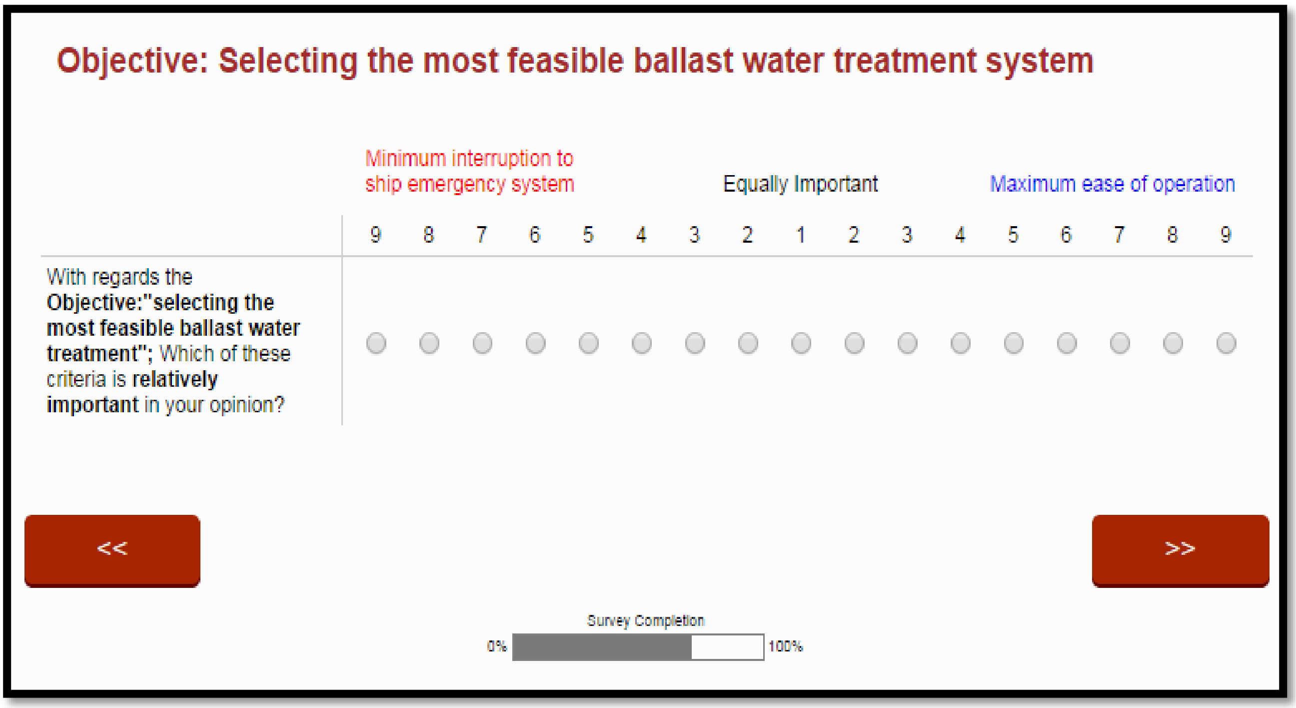
Objective: Selecting the most feasible ballast water treatment system
Minimum interruption to ship emergency system
Equally Important
Maximum ease of operation
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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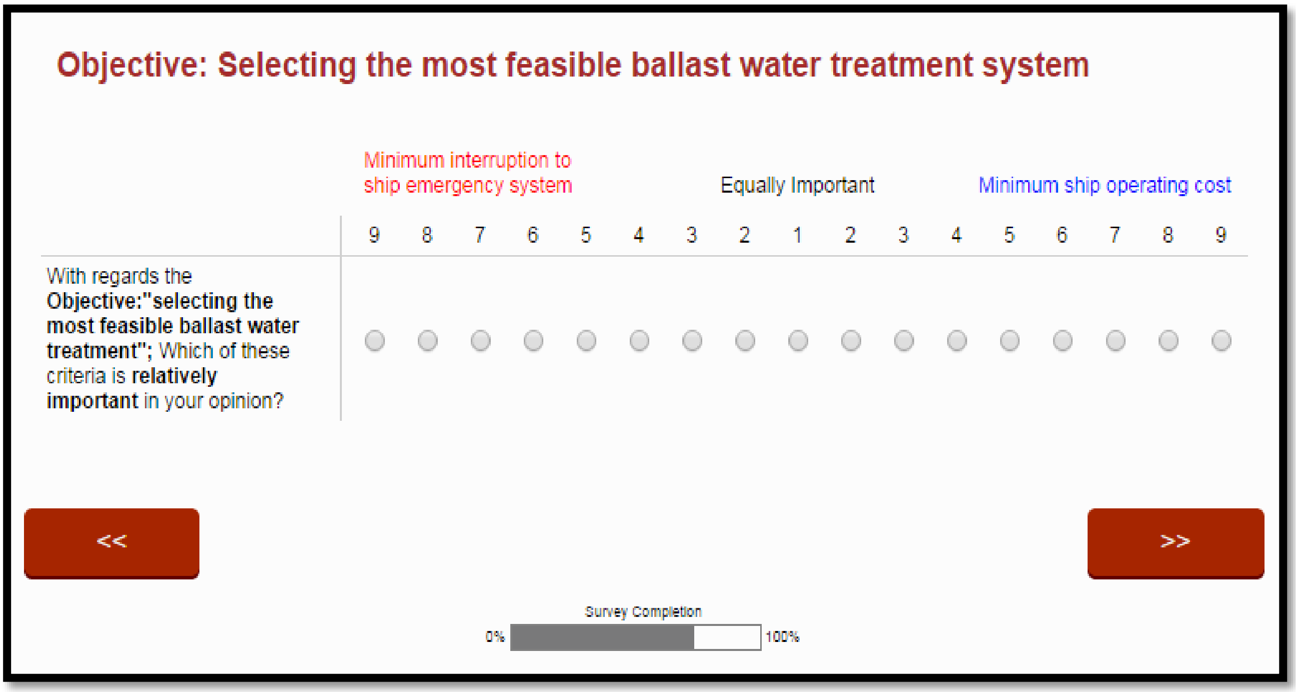
Objective: Selecting the most feasible ballast water treatment system
Minimum interruption to ship emergency system
Equally Important
Minimum ship operating cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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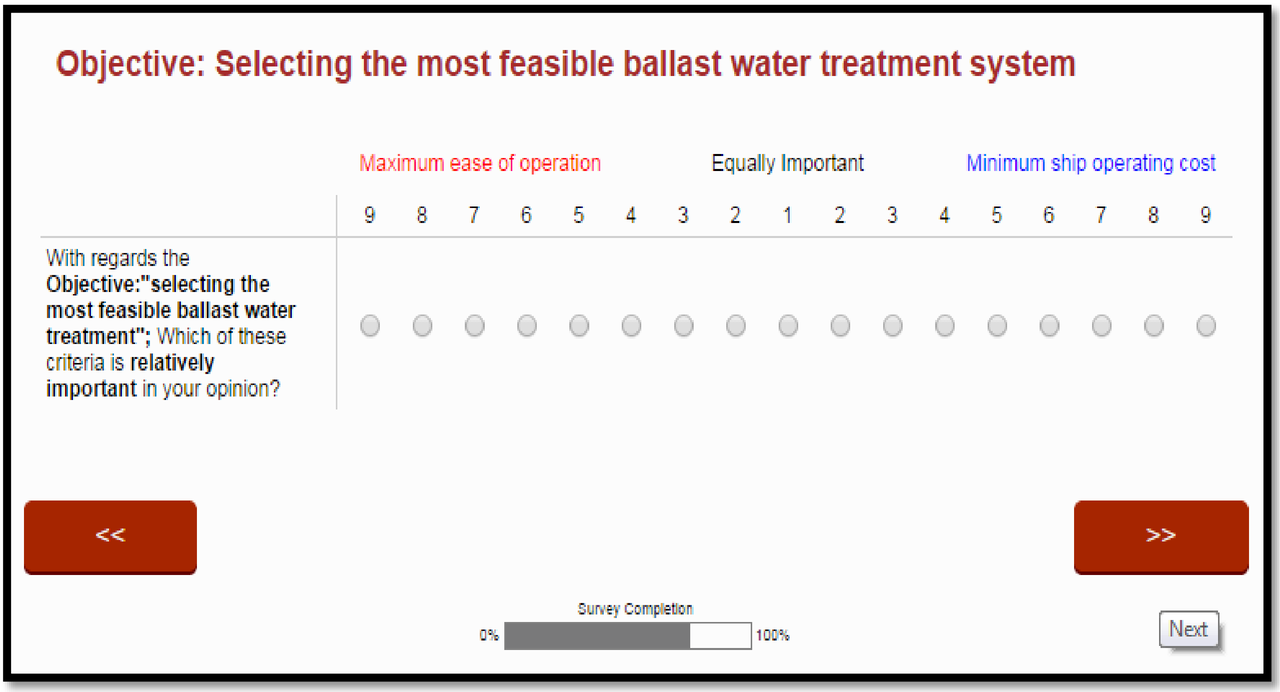
Objective: Selecting the most feasible ballast water treatment system
Maximum ease of operation
Equally Important
Minimum ship operating cost
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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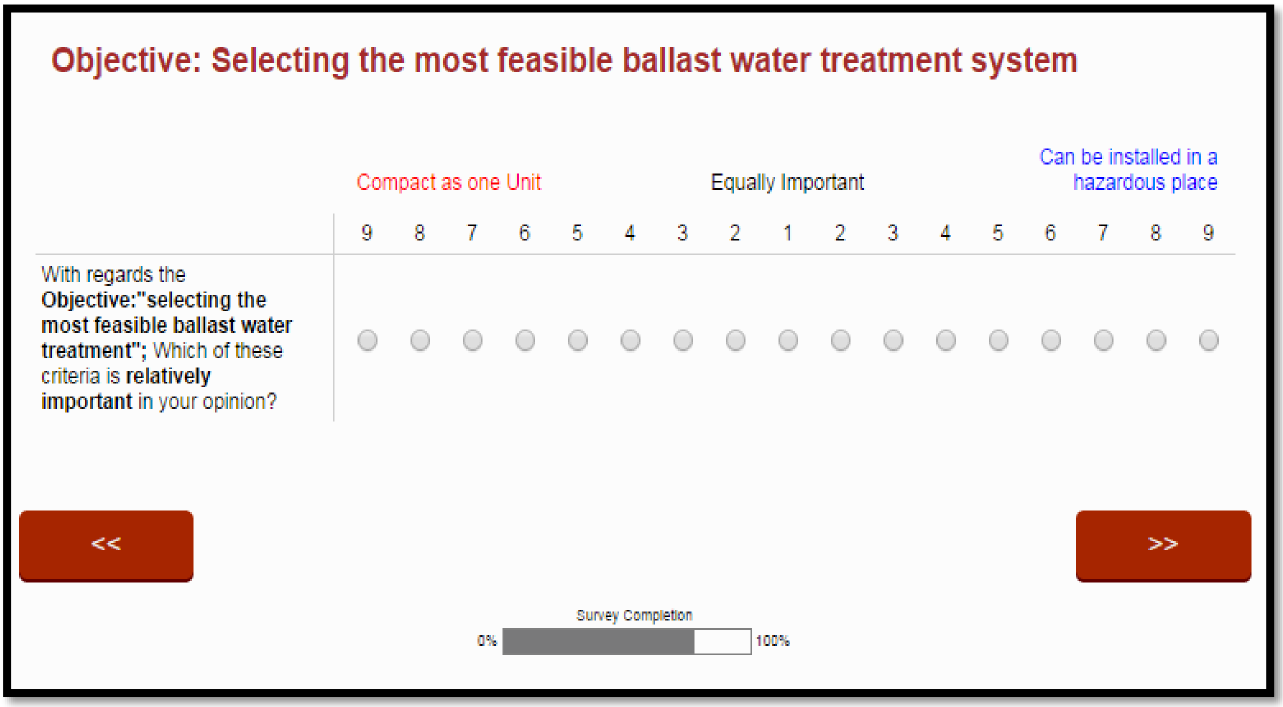
Next


Objective: Selecting the most feasible ballast water treatment system
Compact as one Unit
Equally Important
Can be installed in a hazardous place
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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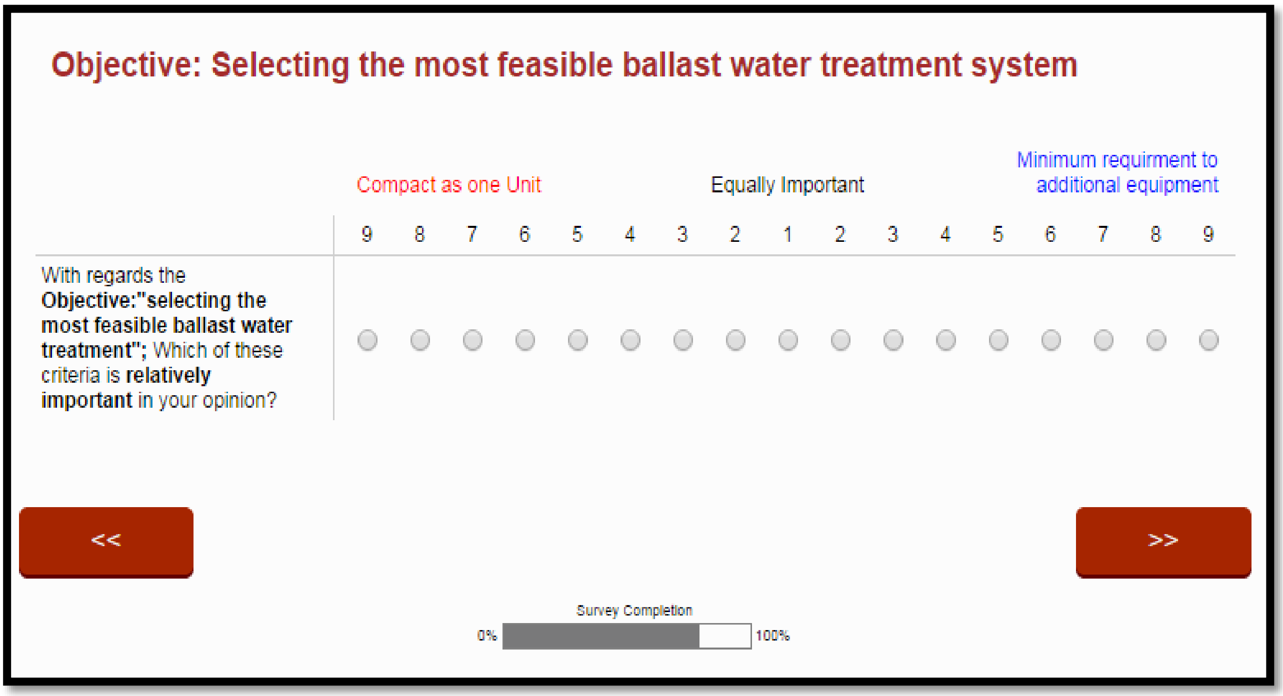
Objective: Selecting the most feasible ballast water treatment system
Compact as one Unit
Equally Important
Minimum requirment to additional equipment
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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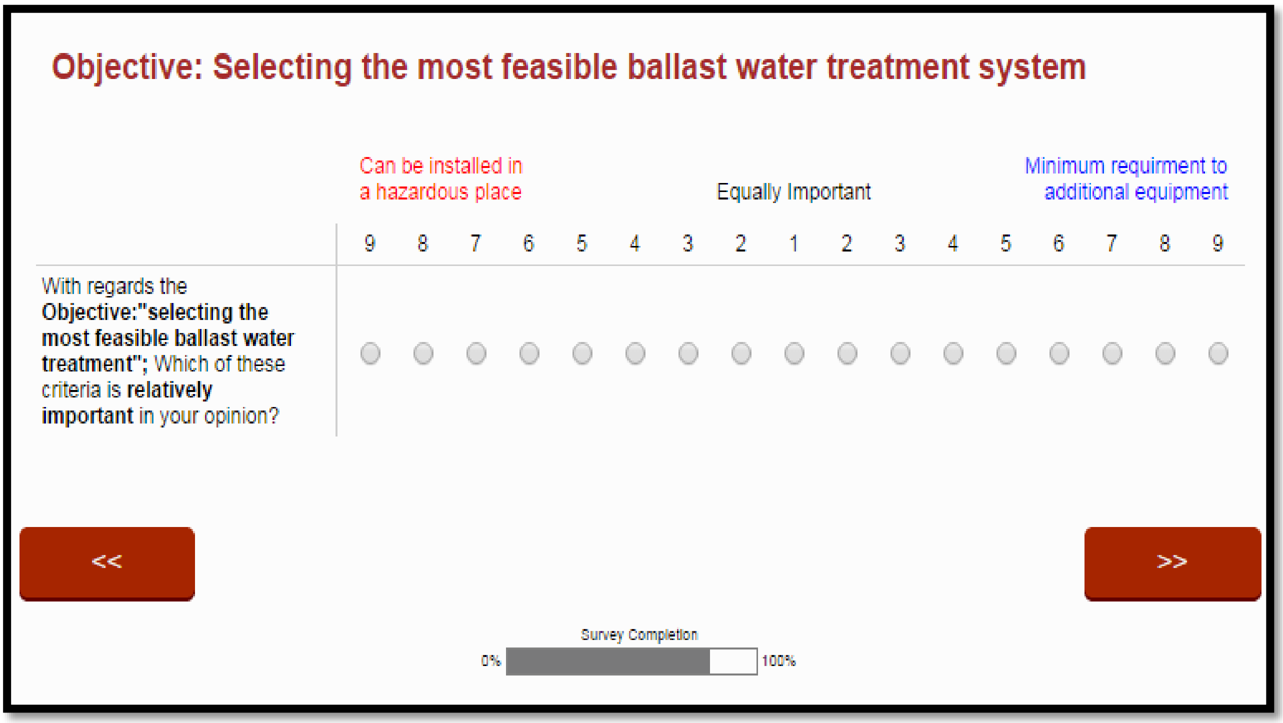
Objective: Selecting the most feasible ballast water treatment system
Can be installed in a hazardous place
Equally Important
Minimum requirment to additional equipment
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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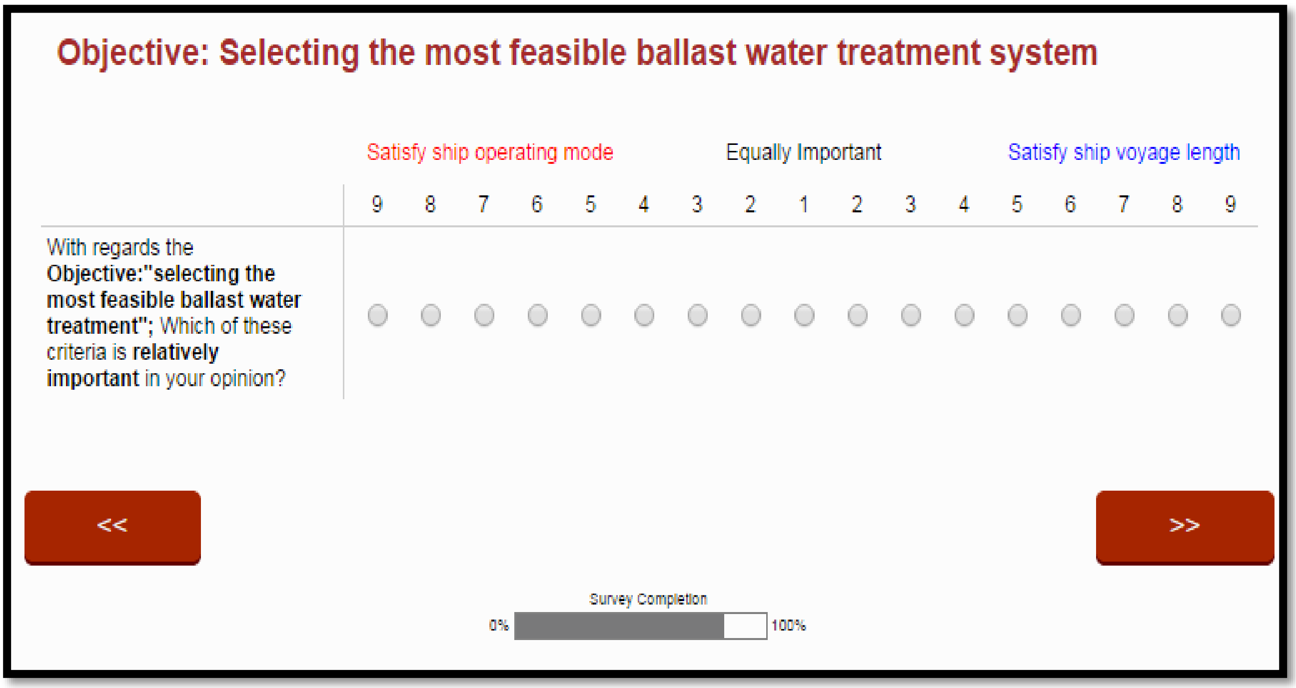
Objective: Selecting the most feasible ballast water treatment system
Satisfy ship operating mode
Equally Important
Satisfy ship voyage length
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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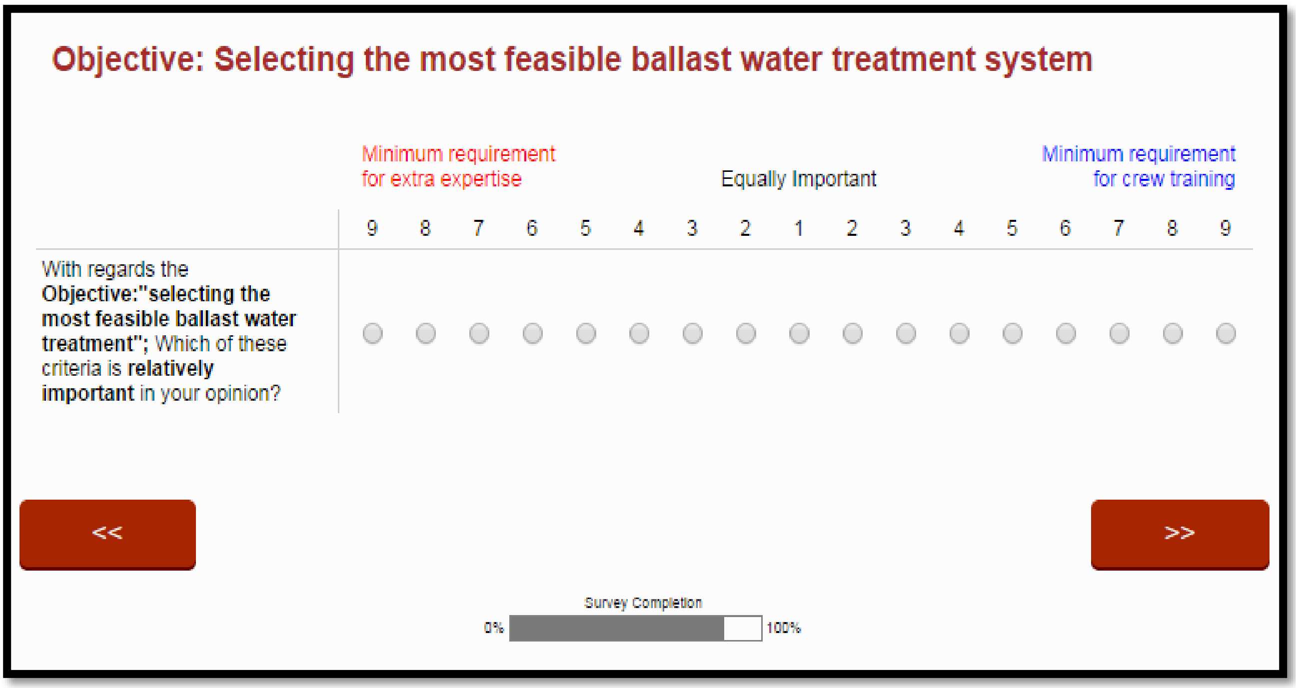
Objective: Selecting the most feasible ballast water treatment system
Minimum requirement for extra expertise
Equally Important
Minimum requirement for crew training
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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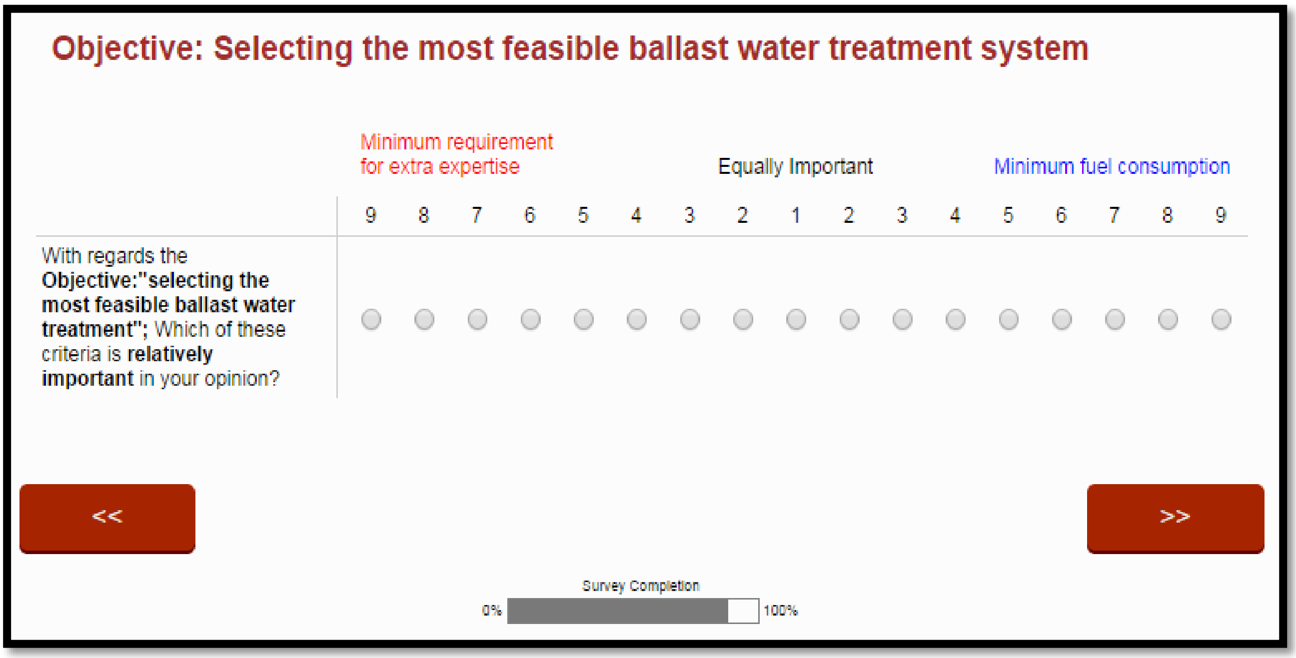
Objective: Selecting the most feasible ballast water treatment system
Minimum requirement for extra expertise
Equally Important
Minimum fuel consumption
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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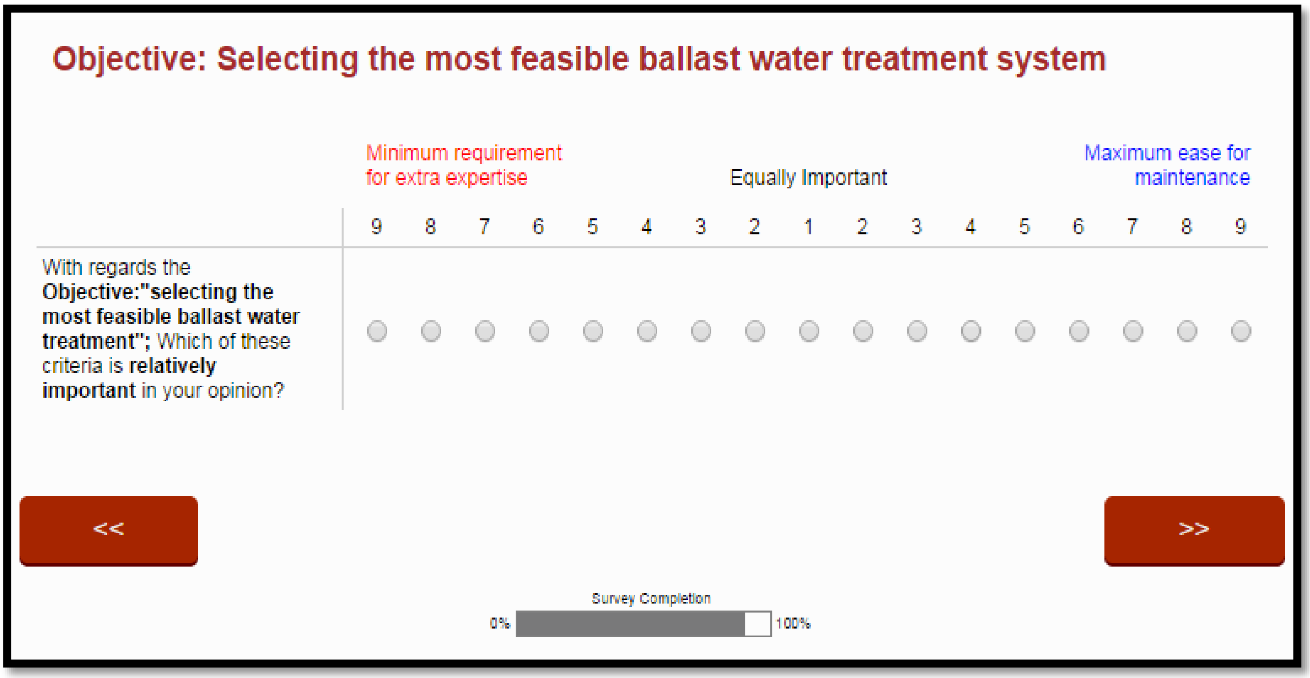
Objective: Selecting the most feasible ballast water treatment system
Minimum requirement for extra expertise
Equally Important
Maximum ease for maintenance
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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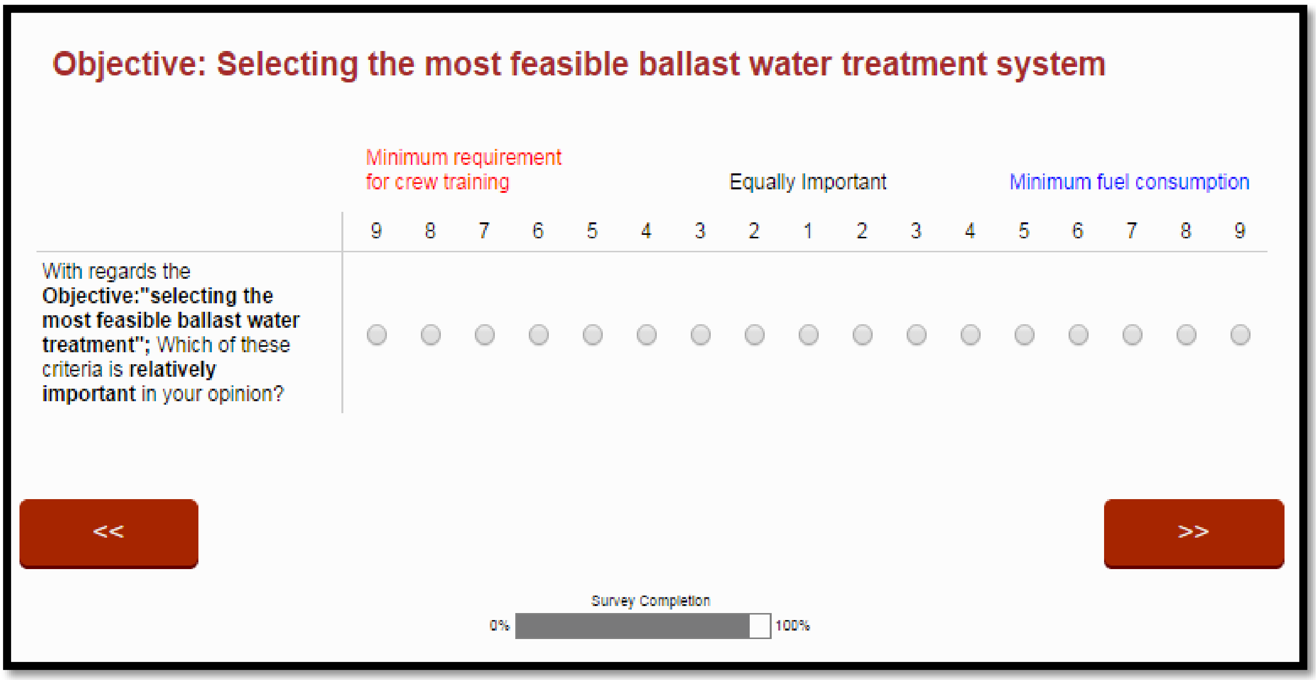
Objective: Selecting the most feasible ballast water treatment system
Minimum requirement for crew training
Equally Important
Minimum fuel consumption
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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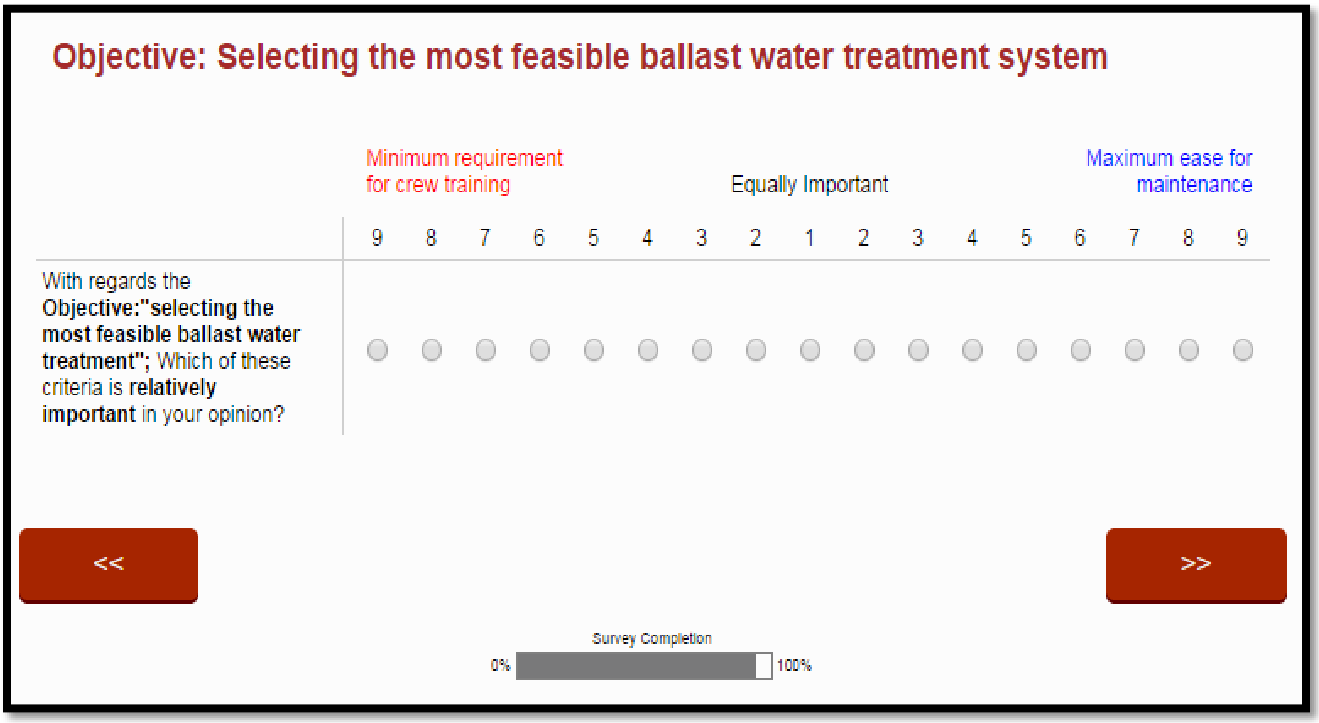
Objective: Selecting the most feasible ballast water treatment system
Minimum requirement for crew training
Equally Important
Maximum ease for maintenance
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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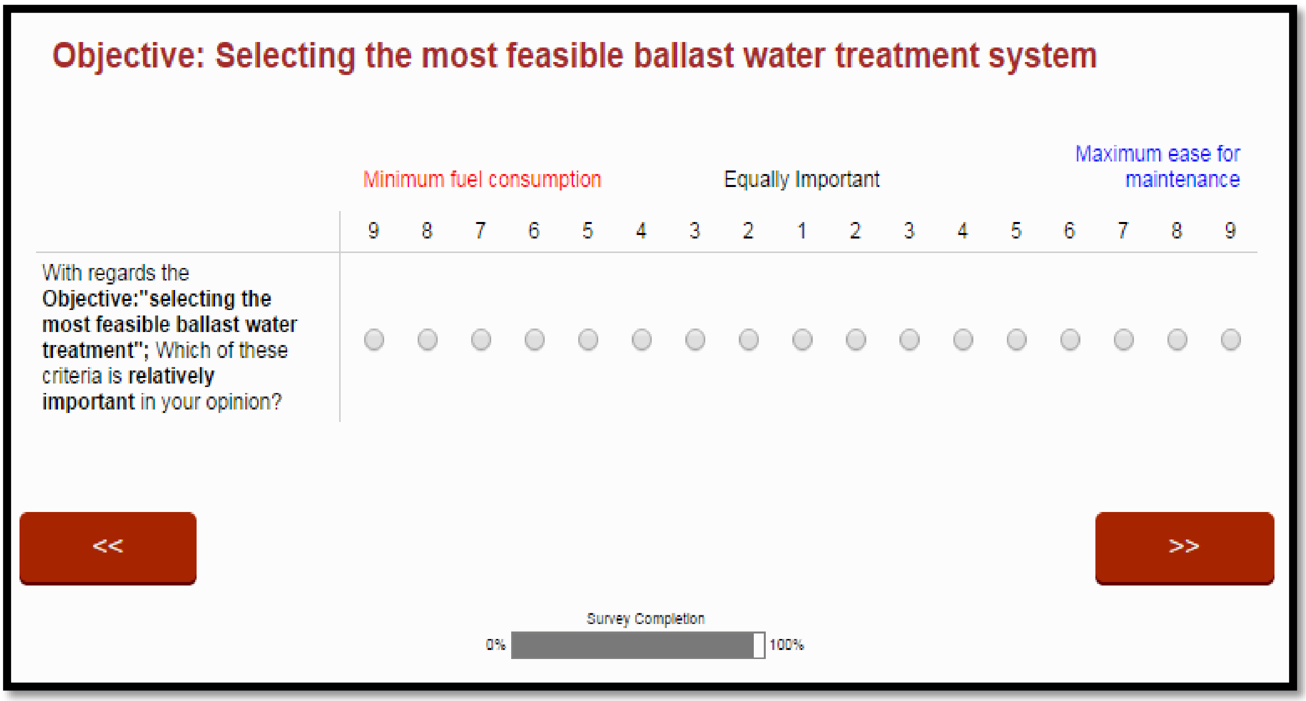
Objective: Selecting the most feasible ballast water treatment system
Minimum fuel consumption
Equally Important
Maximum ease for maintenance
9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9
With regards the Objective:"selecting the most feasible ballast water treatment"; Which of these criteria is relatively important in your opinion?
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Survey Completion
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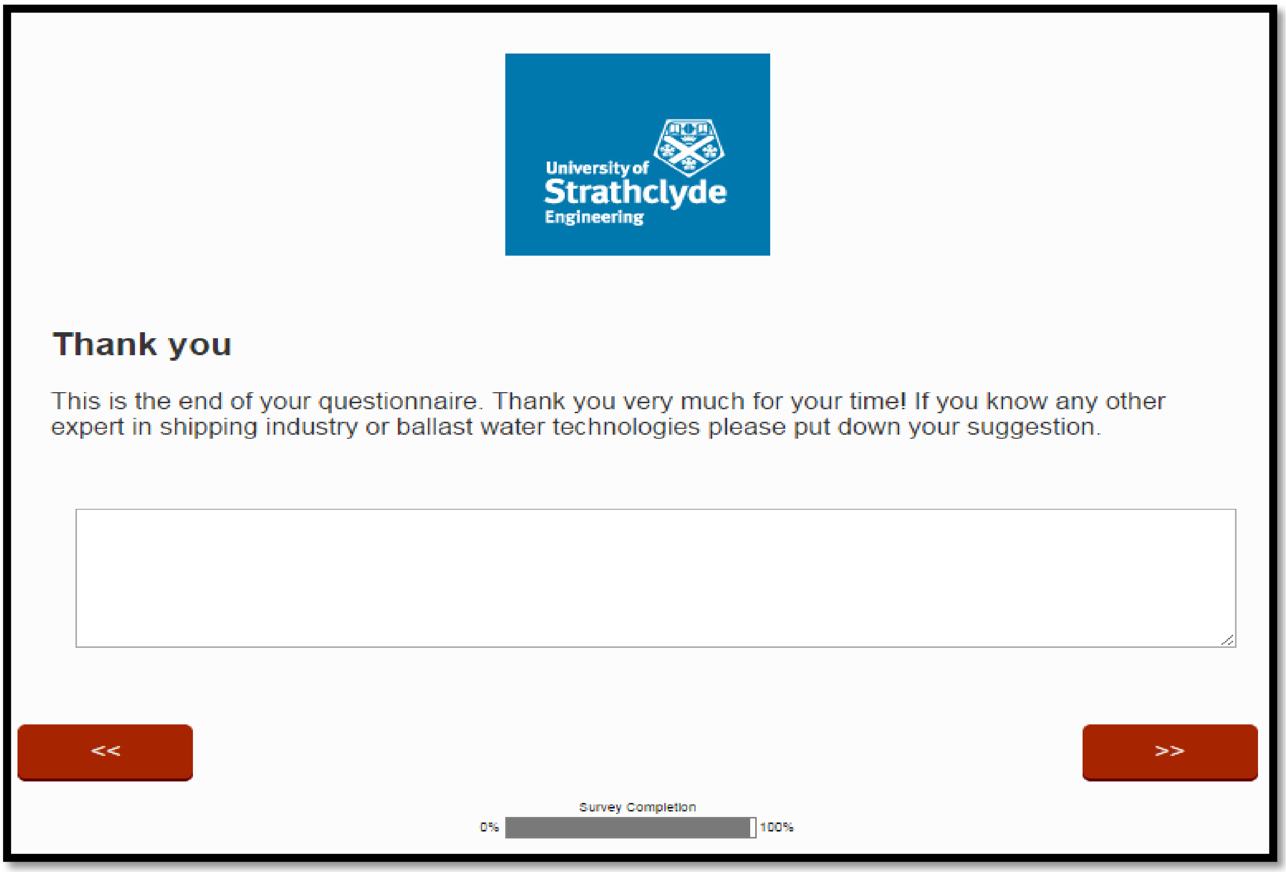
University of Strathclyde Engineering
Thank you
This is the end of your questionnaire. Thank you very much for your time! If you know any other expert in shipping industry or ballast water technologies please put down your suggestion.
<<
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Survey Completion
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100%

Appendix C

Interview validation questions (3rd February 2015).

1. Does the presented result show the applicability of the model as a helpful tool?
2. Please explain your answer of the above question?
3. Do you think that the results obtained by the model were useful?
4. Why do you think that the obtained results are useful or not useful?
5. Have the obtained results matched what was selected or installed into this VLCC?
6. If not, why do you think the selected was different?
7. Do you think that this model can be easily implemented as tool to help you select the most feasible BWTS alternatives for your company's ships?
8. Can you add any comments on the results?

Appendix D

AHP analysis in Microsoft Excel

Any n-rowed square matrix has at least one and at most n distinct eigenvalues. The eigenvalues of a square matrix [A] are considered the roots of the corresponding characteristics equation. The characteristic equation is:

$$D(\lambda) = \det(A - \lambda I) = 0$$

Where: (λ) is eigenvalues; (det) is determinant; (A) is the square matrix ;(I) is the identity matrix.

As mention above, for squared matrix there n distinct eigenvalues and Saaty (1980) established that the largest eigenvalue (λ_{max}) is the principle eigenvalue of A.

To calculate the eigenvector, the principle eigenvalue is substituted in the following equation:

$$Ax = \lambda x$$

Where: (x) is the eigenvector for the principle eigenvalue(λ_{max}). To find the eigenvalues of a large squared matrices. A computer solution of eigenvalues is essential. There are also several software packages available, which will provide the solution. Microsoft Excel can be used to find the solution as follow:

- Define the goal, criteria and alternatives, and then structure the hierarchy
- Build the n x n matrix table as follow, where n is the number of criteria, in the table below we got 3 x 3 matrix. Where C1, C2, and C3 are pairwise criteria compared against each other.

Criteria	C1	C2	C3
C1	1		
C2		1	
C3			1

- Notice that 1s are along the diagonal of the n x n matrix. This is because any criterion compared by the same criterion will equal to 1 : $a_{AA} = 1$,
- Also, the matrix is reciprocal, i.e. $a_{AB} = \frac{1}{a_{BA}}$.
- Saaty (1980) has proposed absolute measurements on a scale of 1 to 9 to be used to score the paired comparisons. This scale is not arbitrarily chosen, but followed by continuous experimentations with large number of scales, proving the high consistency it provided.

Saaty (1980) has given the following definition and explanation for each intensities in the table below:

Importance	Definition	explanation
1	Equal importance	• Two activities contribute equally to objective
2	Weak or slight	
3	Moderate importance	• Experience and judgment strongly favour one activity over another
4	moderate plus	
5	Strong importance	• Experience and judgment strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	• An activity is strongly favoured and its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	• The evidence favouring one activity over another is the highest possible order of affirmation

- Only the upper part of the matrix is required for the comparison using the table above. It is worth noting that, if the criterion in the column is preferred to the criterion in the row, then the inverse of the score is given. Example of numbers are used in the table below.

Criteria	C1	C2	C3
C1	1	**4**	**5**
C2	=1/4	1	**0.5**
C3	=1/5	=1/(0.5)	1

- Notice that a_{23}=0.5 this means that C3 is more important than C2
- After completing the matrix, the next step is to normalise the matrix. This is done by totalling the numbers in each column then is divided by the column sum to yield its normalised score. It should be noted that the sum of each column must equal to 1.

Criteria	C1	C2	C3
C1	0.17	0.75	0.77
C2	0.50	0.19	0.08
C3	0.33	0.06	0.15

- The next step is to find the total of each row which is the sum of each row. Then find the average of each row which is each total divided by n, this is the priority vector (W) of the matrix and the sum must equal to 1.

Criteria	C1	C2	C3	total	Vector of priority (W)
C1	0.17	0.75	0.77	1.69	**0.562**
C2	0.50	0.19	0.08	0.76	**0.255**
C3	0.33	0.06	0.15	0.55	**0.183**

- From the table above C1 is shown to have the highest score (0.562) amongst the other criteria. On other words, C1 is the most import criteria or alternative.
- The next step is checking the consistency of our matrix. The purpose of doing this is to make sure that the original preferences ratings were consistent.
- In order to do that in Microsoft excel, the original matrix A is multiplied by the vector of priority (W) to get what we call W_s i.e.$\{W_s\} = [A] \cdot [W]$. Use the Excel's function matrix multiplication function = MMULT()
- Then find the consistency vector i.e. $cosistency = W_s \cdot \left\{\frac{1}{W}\right\}$. Then find the average of the consistency vector and that is the principle eigenvalue (λ_{max}) of the matrix A. the closer λ_{max} to n (the order of the matrix), the more consistent is the result.
- Saaty (1980) provides for consistency checking of each criterion a consistency index (CI): $CI = \frac{(\lambda_{max} - \mathrm{n})}{(\mathrm{n}-1)}$, where n is the number of criteria (the order of the matrix).
- Saaty (1980) provides further justification, where the CI value is compared with the consistency index of random generated matrices of the same size denoted as random indices (RI). These random indices have been generated at Oak Ridge National Laboratory, for matrices orders of 1 to 15, using a sample size of 100, and further researched at the Wharton School for a sample size of 500 up to 11 matrices. The RI values are given in the table below.

Size of matrix	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

- To calculate the consistency ration (CR) according to Saaty (1980): $\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$. A consistency ratio of 0.10 or less is considered to be acceptable.
- The pairwise comparisons are repeated for each criterion. The normalized eigenvectors are then combined into a matrix of local priorities, which is the multiplication with the

priority vector of one level up, in order to yield local weighted solution, i.e. [local priority matrix]•[priority vector]= [result vector].

- The final product of these steps is a vector, in which the various considered criteria or alternatives have been ranked, and the best decision can be selected.

Appendix E

The Fuzzy Analytic Hierarchy Process (FAHP) application to the 1st developed AHP model.

The results obtained by the 1st developed model indicated that de-oxygenation (0.436) and UV (0.36) have emerged as the most feasible BWTS alternatives with de-oxygenation more preferred than both UV and ozone (0.20) (For full study details see ALHababi et al (2014a)). The results obtained by using AHP only were tested using Chang's (1996) method, i.e. typical Fuzzy Analytic Hierarchy Process (FAHP) was used to achieve better results. The FAHP application is discussed next.

Fuzzy sets and fuzzy numbers

Fuzzy set theory was first introduced by Zadeh (1965) as an approach to deal with vagueness and uncertainty of human thought due to imprecision. A fuzzy set is a class of objects with a continuum of grades of membership ranging from 0 to 1 (Zadeh, 1965). A fuzzy number $\tilde{A}$ on real numbers R is said to be a triangular fuzzy number (TFN), and it is defined by its membership function $U_{\tilde{A}}$ (x):

$$U_{\tilde{A}}(x) = \begin{cases} (x-l)/(m-l), & l \le x \le m, \\ (u-x)/(u-m), & m \le x \le u, \\ 0, & otherwise \end{cases} \qquad (1)$$

Where $l \le m \le u$,stand for the lower, modal and the upper support value of the TFN $\tilde{A} = (l, m, u)$. A triplet fuzzy number is shown in Figure 1.

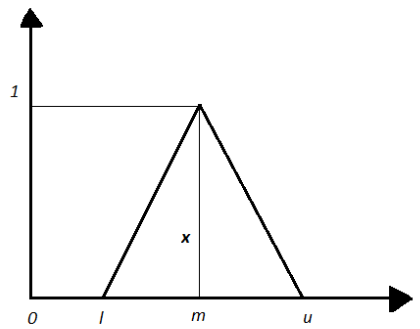

Figure 1: Membership function of a triangular number $\tilde{A} = (l, m, u)$

Considering two TFNs for example M_1 and M_2, $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$. Their operational lows are as follows:

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \qquad (2)$$

$$(l_1, m_1, u_1) \odot (l_2, m_2, u_2) \approx (l_1 l_2, m_1 m_2, u_1 u_2) \qquad (3)$$

$$(\lambda, \lambda, \lambda) \odot (l_1, m_1, u_1) = (l_1 \lambda, m_1 \lambda, u_1 \lambda) \;\; = \;\; \lambda > 0, \lambda \in R \qquad (4)$$

$$(l_1, m_1, u_1)^{-1} \approx \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \qquad (5)$$

Extent analysis method on fuzzy AHP

Let $X = \{x_1, x_2, \ldots . x_n\}$ be the object set, and $U = \{u_1, u_2, \ldots . u_n\}$ be the goal set. According to Chang (1996), each object (x_i) is taken and extent analysis for each goal (u_i) is performed respectively. Therefore, we can get *m* extent analysis values for each objective, with the following signs:

$$M_{g_i}^1, M_{g_i}^2, \ldots, M_{g_i}^m, i = 1,2, \ldots . n, \qquad (6)$$

Where all the $M_{g_i}^j$(j=1, 2,…, *m*) are TFNs.

The value of fuzzy synthetic extent with respect to the ith objective is defined as:

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \odot \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1} \qquad (7)$$

According to (Bozbura and Beskese, 2007), to obtain$\sum_{j=1}^{m} M_{g_i}^j$, perform the fuzzy addition operation, given by equation (2), of *m* extent analysis values for a given matrix such as:

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_{ij}, \sum_{j=1}^{m} m_{ij}, \sum_{j=1}^{m} u_{ij}\right), \;\; i = 1,2, \ldots, n \qquad (8)$$

And to obtain$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1}$, perform the fuzzy addition operation equation (1) of $M_{g_i}^j$*(j=1,2,…,m)* values such as given: $\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j =$

$$\left(\sum_{i=1}^{n} \sum_{j=1}^{m} l_{g_i}^j, \sum_{i=1}^{n} \sum_{j=1}^{m} m_{g_i}^j, \sum_{i=1}^{n} \sum_{j=1}^{m} u_{g_i}^j\right) \qquad (9)$$

And then compute the inverse of the vector in equation (9) above; perform the operation equation (5), such as given by:

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(1/\sum_{i=1}^{n}\sum_{j=1}^{m} u_{g_i}^{j}, 1/\sum_{i=1}^{n}\sum_{j=1}^{m} m_{g_i}^{j}, 1/\sum_{i=1}^{n}\sum_{j=1}^{m} l_{g_i}^{j}\right) \quad (10)$$

The degree of possibility of $M_1 \geq M_2$ is defined as:

$$V(M_1 \geq M_2) = SUP_{x\geq y}[min((\mu_{M_1}(x), \mu_{M_2}(y))] \quad (11)$$

When a pair (x,y) exist such that $x \geq y$ and $\mu_{M_1}(x) = \mu_{M_2}(y) = 1$, then we have $V(M_1 \geq M_2) = 1$. Since M_1 and M_2 are convex fuzzy numbers we have that:

$$V(M_1 \geq M_2) = 1 \;\; iff \; m_1 \geq m_2, \quad (12)$$

$$V(M_1 \geq M_2) = hgt\,(M_1 \cap M_2) = \mu_{M_1}(d),$$

Where, *iff* means if and only if, *d* is the ordinate of the highest (hgt) intersection point D between μ_{M_1} and μ_{M_2} as shown in Figure 2.

When $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the ordinate of D is given by:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1, & if\; m_2 \geq m_1 \\ 0, & if\; l_1 \geq u_2 \\ \frac{(l_1 - u_2)}{(m_2 - u_2) - (m_1 - l_1)}, & Otherwise \end{cases}$$

(13)

To compare M_1 and M_2, we need both the values of $V(M_1 \geq M_2) and\; V(M_2 \geq M_2)$.

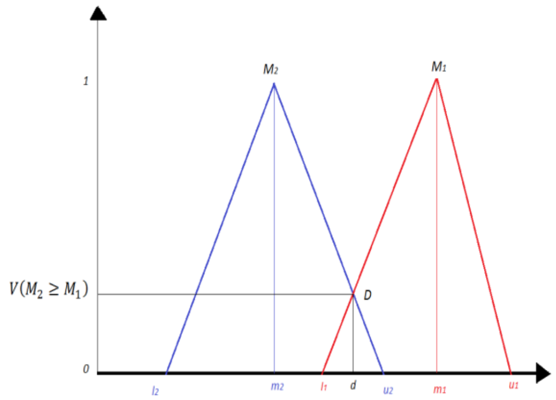

Figure 2: The intersection between M_1 and M_2

The degree possibility for a convex fuzzy number to be greater than *k* convex fuzzy numbers M_i (*i=1, 2,…k)* can be defined by:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1)\; and\; (M \geq M_2) and \dots..and (M \geq M_k)] = \min V\,(M \geq M_i), i = 1,2, \dots, k. \quad (14)$$

Assume that:

$$d'(A_i) = \min V\,(S_i \geq S_k) \quad (15)$$

for $k = 1,2,\dots,n)$ $k \neq i$. Where A_i (i=1, 2,….,n) are n elements.

Then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \ldots . d'(A_n))^T, \quad (16)$$

Where A_i (i=1, 2,….,n) are n elements.

Via normalization, we get the normalized weight vectors:

$$W = (d(A_1), d(A_2), \ldots . d(A_n))^T \quad (17)$$

Where W is a non-fuzzy number. Normalizing fuzzy weight vector is obtained using equation:

$$W = \frac{W'_n}{\sum_{i=1}^{n} W'} \quad (18)$$

Where (i=1, 2,….,n).

The created matrix tables for both the identified ballast water criteria and the ship related criteria in the 1st model study (ALHababi et al (2014a)) were converted into a coincided TFNs using Table1.

Table 1: Translation crisps obtained from the matrix tables by ALHababi et al (2014a) into the triangular fuzzy numbers (TFNs) (source, adopted and modified by author from (Ho, 2011))

AHP priority Scale	Linguistic scale	Positive TFNs	Reciprocal TFNs
9	**Absolutely important**	(9,9,9)	(1/9,1/9,1/9)
8	Intermediate	(7,8,9)	(1/9,1/8,1/7)
7	**Very strong**	(6,7,8)	(1/8,1/7,1/6)
6	Intermediate	(5,6,7)	(1/7,1/6,1/5)
5	**Strong**	(4,5,6)	(1/6,1/5,1/4)
4	Intermediate	(3,4,5)	(1/5,1/4,1/3)
3	**Weak**	(2,3,4)	(1/4,1/3,1/2)
2	Intermediate	(1,2,3)	(1/3,1/2,1)
1	**Equally important**	(1,1,1)	(1,1,1)

Numerical results and Discussions

By using equations (7), (8), (9) and (10) we obtained the values of fuzzy synthetic extent with respect to the five ballast water related criteria calculated in Table 2.

Table 2: the values of fuzzy synthetic extent with respect to the five BWTS related criteria are denoted by S1, S2, S3, S4 and S5 respectively.

S1	(0.1567, 0.2058, 0.2680)
S2	(0.3050, 0.4287, 0.5847)
S3	(0.0855, 0.0986, 0.1164)
S4	(0.1271, 0.1429, 0.1624)
S5	(0.1080, 0.1238, 0.1461)

By using equations (12) and (13), the degree of possibility of the fuzzy synthetic extent is calculated as shown in Table 3.

Table 3: The obtained degree of possibility of S*i* over S*j* (*i* ≠ *j*) for five BWT related criteria.

$V(S_1 \geq S_2)$	0	$V(S_2 \geq S_1)$	1	$V(S_3 \geq S_1)$	0	$V(S_4 \geq S_1)$	0.2405	$V(S_5 \geq S_1)$	0
$V(S_1 \geq S_3)$	1	$V(S_2 \geq S_3)$	1	$V(S_3 \geq S_2)$	0	$V(S_4 \geq S_2)$	0	$V(S_5 \geq S_2)$	0
$V(S_1 \geq S_4)$	1	$V(S_2 \geq S_4)$	1	$V(S_3 \geq S_4)$	0	$V(S_4 \geq S_3)$	1	$V(S_5 \geq S_3)$	1
$V(S_1 \geq S_5)$	1	$V(S_2 \geq S_5)$	1	$V(S_3 \geq S_5)$	0.4538	$V(S_4 \geq S_5)$	1	$V(S_5 \geq S_4)$	0

By using equation (15), we obtain minimum degree of possibility as stated below:

$d'(S_1) = \min V\left(S_1 \geq S_{2,}S_{3,}S_{4,}S_5\right) = \min(0,1,1,1) = 0$

$d'(S_2) = \min V\left(S_2 \geq S_{1,}S_{3,}S_{4,}S_5\right) = \min(1,1,1,1) = 1$

$d'(S_3) = \min V\left(S_3 \geq S_{1,}S_{2,}S_{4,}S_5\right) = \min(0,0,0,0.4538) = 0$

$d'(S_4) = \min V\left(S_4 \geq S_{1,}S_{2,}S_{3,}S_5\right) = \min(0.2405,0,1,1) = 0$

$d'(S_5) = \min V\left(S_5 \geq S_{1,}S_{2,}S_{3,}S_4\right) = \min(0,0,1,0) = 0$

Therefore from equation (16), the weight vector is obtained:

$W' = (0,1,0,0,0)^T$

After the normalization process using equation (18), the weight vector with respect to the decision for the ballast water related criteria can be presented as follows:

$W = (0,1,0,0,0)^T$

The same steps above were performed for each BWTS alternative namely (de-oxygenation, UV, and ozone) with respect to the identified ballast water related criteria. The resulted performance by the weigh vector of each BWTS alternative is shown in Table 4.

Table 4: The performance of the three ballast water treatment (BWTS) alternatives

Weight Vector	Cost	Safety	Bio-efficiency	Regulation	practicality
Ozone	**0**	**0**	**0**	**0.3333**	**0**
UV	**0**	**0.5**	**1**	**0.3333**	**1**
De-oxygenation	**1**	**0.5**	**0**	**0.3333**	**0**

Finally, according to Chang (1996) method, by adding the obtained weights of the three BWTs with respect to each corresponding criteria, then multiplying them by global obtained weight, the final ranking score is obtained as shown in Table 5.

Table 5: The obtained vector of ranking three ballast water treatment system alternatives and showing that both de-oxygenation and UV BWTS alternatives as the most feasible ballast water options

Ozone	**0.00**
UV	**0.50**
De-oxygenation	**0.50**

The final vector shown in Table 5 indicates that both de-oxygenation and UV alternatives are considered the most feasible ballast water options in this study. It is worth noting that, the FAHP approach used in this study is consistent with obtained results by using the AHP alone in terms of selecting the most feasible ballast water alternative, i.e. de-oxygenation and UV BWTS alternatives and rejecting the least preferred or weighted one, i.e. ozone treatment. However, there is no indication why would the results obtained by the FAHP be considered better than using the AHP method only.