Holistic Modelling of LNG Carrier Systems

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To my family,

For their understanding, support and care

Thank you very much

I love you all

Declaration

No portion of the work referred to in this dissertation has been submitted in support of an application for another degree or qualification of this or any other institution of learning.

Md Redzuan ZOOLFAKAR May 2012

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Abstract

As the human population increases in parallel with an increase in the standard of living, the world energy demand also continually grows every year. Fossil fuels are the major components contributing to this energy supply. Natural gas, one of the fossil fuels, has shown promising growth due to it price and lower pollutant emissions compared to other fossil fuels.

One option for transporting natural gas is the use of Liquefied Natural Gas (LNG) carriers. The LNG carrier is one of the most expensive, complex and potentially hazardous cargo carriers that are operating across the world's oceans due to its cargo, thus proven components are required to build this type of ship.

There are seven main components involved in constructing an LNG carrier and they are manufactured by a range of different companies. This situation has created a competitive environment for this industry; however it has also introduced a new challenge to the shipbuilder, engineer and ship-owner in terms of selecting the right components. For a new ship design, there would typically be an incremental change in one or more technology elements from a base design and over time this may result in a less than optimum design.

This thesis therefore aims to develop a holistic methodology that can be employed in order to help the ship-owner in particular to select the right combination components for an LNG carrier to rationalise the fleet size, minimise overall costs of construction and operation, and control the total mass of pollutant emission products in preliminary design stage.

This methodology is based on the mutual symbiosis between the tools used: namely a comprehensive ship system simulation method, an artificial neural network (ANN) evaluation process and an integrated ANN based multi-objective optimisation process. It is a comprehensive methodology that can be applied to all types of ships, although in this study, it focuses on LNG carriers.

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Nomenclature

Uppercase Symbols

A	Area
ABS	American Bureau of Shipping
ANN	Artificial Neural Network
Aux	Auxiliary
B	Breadth
BOG	Boil Off-Gas
BP	British Petroleum
C	Carbon
CAD	Computer Aids Design
CFD	Computational Fluid Dynamics
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
CS1	Combined System Number 1
D	Depth
EIA	International Energy Outlook
GE	General Electric
GTC	Gas Turbine Ship
H_2O	Water
HD	High Duty
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IGC	The International Code for Construction and Equipment of Ship Carrying Liquefied Gases in Bulk
IMO	International Maritime Organisation
INVAR	Nickel Steel
IOCS	Institute of Chartered Shipbrokers
ITTC	International Towing Tank Conference
L	Length
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
LCC	Life Cycle Costs
LCCA	Life Cycle Costs Analysis
LD	Low Duty
LNG	Liquefied Natural Gas
LWS	LNG World Shipping
MER	Marine Engineering Review
MOGA	Multi-objective Genetic Algorithm
MSE	Mean Square Error
N	Required Economic Life
N_2	Nitrogen Gas
NGH	Natural Gas Hydrate
No.	Number
NO_x	Nitrogen Oxide
NPV	Net Present Value

O_2	Oxygen Gas
OSL	Optimisation Software Language
P	Power
PB	Brake Power
PER	Pollutant Emission Ratio
R	Resistance
RA	Model-Ship Correlation Resistance Factor
RANSE	Reynolds-Averaged Nervier-Stokes Equation
RAPP	Resistance of Appendages
RFR	Required Freight Rate
RFR	Frictional Resistance
ROPAX	Roll-on/Roll-off Passenger Vessels
RPUF	Reinforced Polyurethane Form
R_t	Thermal Resistance
RTR	Transom Stern Resistance
RW	Wave-Making and Wave-Breaking Resistance
SB	ShipbuildingHistory
SECA	Sulphur Emission Control Area
SFC	Specific Fuel Consumption
SOLAS	Safety of Life at Sea
SO_x	Sulphur Oxide
SPB	Self-supporting Prismatic Shape IMO Type B tank
SPE	Specific Pollutant Emission
SRC	Sea Rates Dot Com
SSPA	StatensSkeppsprovningsAnstalt
SubVI	Sub-Virtual Instruments
T	Temperature
TLC	Total Life Care
TNA	The Naval Architect
VI	Virtual Instrument
W	Work Done
W	Weight
W_{st}	Weight of the Ship Steel
X	Slope X
Y	Slope Y

Lowercase Symbols

d	Draft
e.g.	'Exempli Gratia' or 'For Example'
f(x)	Objective Function
h	Thermal Convection Coefficient
h	Enthalpy
i	Rate of Return
i.e.	'Id Est' or 'That Is'
k	Thermal Conductivity Coefficient
m	Mass
$\dot{m}$	Mass Flow Rate
$\dot{m}_{pe}$	Mass Flow Rate of Pollutant Emission
nm	Nautical Mile
q	Heat Transfer
$\dot{q}$	Heat Transfer Flow Rate
r	Regression
x	Thickness of Material
y	Data Output

Greek Symbols

Δ	Difference
Δ	Displacement
Σ	Total
α	Constant
η	Efficiency
η_i	Isentropic Efficiency

1. Introduction

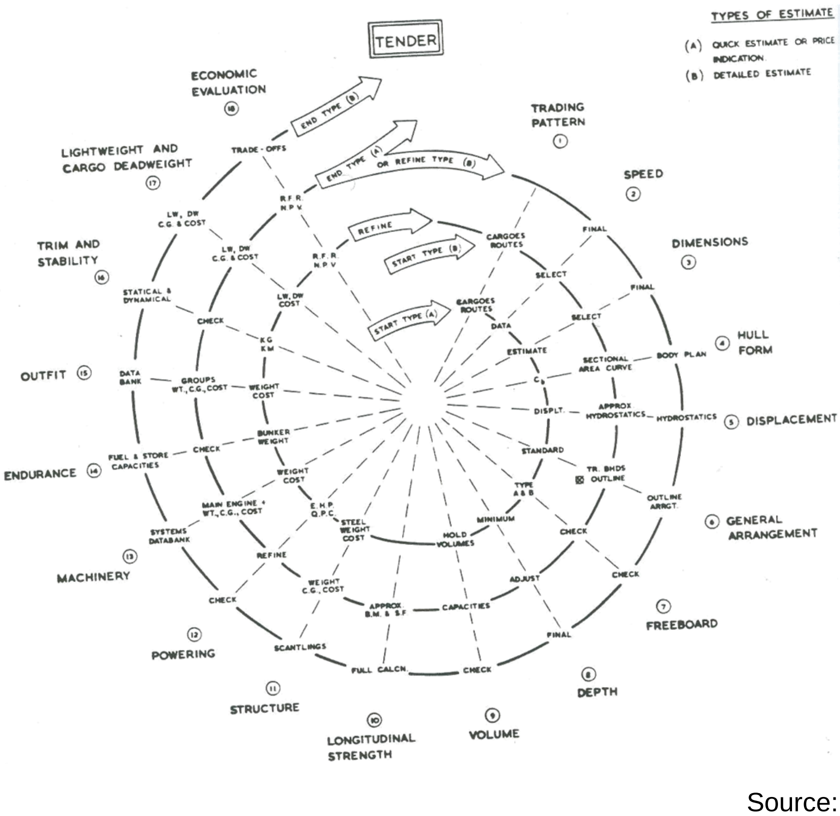
1.1. Background of the Study

Ships are the oldest type of mechanical transportation on earth. They date back to 4000 BC when ancient Egyptians were using reeds to build sailing boats in order to cross the river Nile. Since that time, the development of ships has expanded from its initial use as a mere form of personal transport to its present use as a principal mode of moving cargo and passengers around the world. The first known activity of sea trading was developed around 3000 BC between Mesopotamia, Bahrain and the Indus River. Oil and dates were traded for copper and ivory (Stopford, 2009).

As time passed, the development of the vessel was changed from the construction of wooden ships to ships built from various materials such as steel, aluminium and fibreglass. Interestingly, the general method of their overall design has remained largely unchanged. A new ship is often designed by mimicking a previous vessel which is usually a full scale ship. This is an ‘evolutionary’ approach to design. Thus this approach cannot be adapted to other types of ships because the use of copying in the design process is only for arrangements that are similar to the model ship. In addition this method does not allow for evaluations in, for example, total ship cost to be performed. By contrast, the modern approach focuses more on capital and operational costs in maritime economics. Thus it takes into account the market demand, emergence of new technologies in the components and alternative design methods in order to reduce the total costs (Buxton, 1976). For a new ship design, there would typically be an incremental change in one or more technology elements from a base design and over time this may result in a less than optimum design.

Considering a scenario where a ship-owner requests a tender for a new ship from a shipbuilder, frequently the shipbuilder will use existing data from their recent experience and match them, with some manipulation, to the new enquiry in order to produce the new design and estimated cost. If the tender is accepted, a contract between the ship builder and ship owner is put in place and a fully detailed ship design will then be worked up. It may seem that the ship design process is simple, however in practice it is a complex task and the best way to understand the initial stages of the ship design process is through the so-called 'Ship Design Spiral'.

The ship design spiral is actually the same as the general ship design diagram model however it reflects the iterative design adjustment process of progressive refinement. This is a widely accepted, systematic, progressive approach model which was introduced by Evans in 1959 (Evan, 1959). The sequence and decision making process to select basic components for the design process can be achieved over a period of time (over some iterations). As the process progresses, it will increase the details in each pass around the spiral until they converge to the required solution and numeric values. Another similar more refined spiral was introduced by Buxton (1976) but this time, it incorporated economic issues. Hence, the ship design spiral is not only focussed on systematic explanation of the theoretical process of ship design development, but it also can be used practically as a tool in the industry. Figure 1-1 illustrates Buxton's ship design spiral.



Source: Buxton,1976

Figure 1-1: Buxton's Ship Design Spiral

Generally, the ship design spiral approach is a point-based design because the results produced only lead to a single point, a single configuration, in the design space. Parsons (2003) has pointed out that the main disadvantage of this approach is that it fails to produce a global optimal solution, i.e., the best economic combination of components, and thus cannot guarantee the best solution. For example, if the ship-owner has decided to buy a certain type of engine, other parameters and components have to be compromised in order to produce the optimal combination of components in order to achieve the given targets. Alternative approaches to ship design which manage the global optimal solution should be considered and one such approach has been proposed in this study.

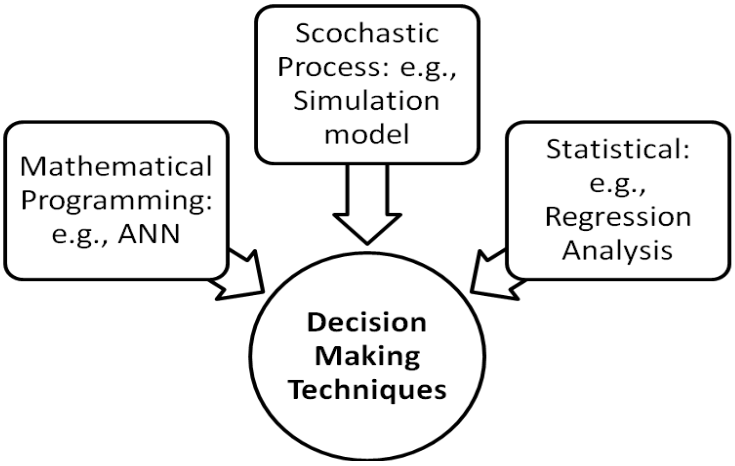
By its nature, ship design is complex due to the high degree of interaction among the many disciplines (Papanikolaou, 2009). In principle, the ship design procedure may be classified into two main phases; detailed and preliminary designs. The detailed design phase is referred to as producing the selected principal design features of the ship. The formulation and calculations are established and ready to use.

The Preliminary design phase is referred to as the decision making process at the early stage (the stage of the ship-owner and shipyard discussing a possible contract). This category has often been overlooked, but it is actually the critical stage for the ship-owner to make major decisions on the dimensions and components which should be selected. Selecting the most economical design components does not necessarily produce the best results for given targets, however gaining a holistic understanding of the engineering economics is far more important in order to achieve the objective functions. In order to appreciate the decision making technique for ship design, it is very useful to understand its background.

1.2. Decision Making: Background

In the real world, everyone is required to make decisions, whether they realise it or not and whether large or small, at any given time and location. In most cases, the aims of these decisions are either to minimise effort or cost or to maximise the desired gain or profit. This process can occur by trial and error or by adopting a more systematic approach. In a systematic, clearly thought-out approach, the effort required or the gain desired is a functional relationship *(x),* of a set of variables. The variables may be separated into independent and dependent variables. Independent variables, sometimes termed decision variables, are variables over which one has some degree of control e.g. length of the perpendicular and speed, whereas the dependent variables or parameters are the results of the independent variables being manipulated e.g., operational costs and amount of boil-off gas produced.

In reality, there is no single method that claims that it can solve all types of decision making problems perfectly. As a result, many decision making methods have been developed to solve specific groups of different problems, as illustrated in Figure 1-2. According to Bertram (2003), the actual method used in addressing the decision making process can be classified as being one of two approaches, these are the Direct Search and the Steepness (Gradient based) approaches. In the Direct Search Approach, solutions are created by varying the parameters either systematically or randomly. The best results are taken as being the estimated optimum for that particular problem. However, the major problem with this approach occurs when the number of variables increases, and so also does the computer time required producing the solutions. The alternative is the Steepness Approach; in which solutions are generated based on information from the specified functional relationships. When the derivative approaches zero, the estimated optimum solution for the problem is considered to have been found. This method is more efficient than the direct search; hence most ship design problems have been undertaken using this approach.



Source: Roa, 1996

Figure 1-2: Decision Making Techniques

The decision making process can be defined as the act of finding the best solution, where ‘best’ is defined by the analyst, for any problem from a set of choices within a given set of constraints (Bertram, 2003). A constraint is a restriction or limitation or boundary defined for the problem variables to ensure that the solutions that are obtained are technically sound and physically or economically feasible. The constraints represent the functional relationship between the independent and dependent variables satisfying physical restrictions and practical or resource limitations. Any consideration of the constraints requires the design to remain in static or dynamic equilibrium. In this study, the constraints are formulated in static equilibrium to satisfy the physical and resource limitations; including regulations from international law and classification society restrictions. There are no special formulae or methods to formulate a constraint in all problems; hence the researcher must have a full understanding the problem that they are dealing with. As a result, the investigation of the decision making process will focus within reasonable limits under the appropriate constraints.

Generally, constraints can be sub-divided into two types: Behavioural or Functional, and Geometric or Side Constraints (Rao, 1996). Behavioural constraints refer to the behaviour of the system’s performance, whereas side constraints represent the physical limitations set for the problem. According to Deb (2005), each of these constraints can further be classified into two broad types: equality and inequality types. An equality constraint is a functional relationship matching the exact resource value. The opposite of this function is an inequality type.

The act of finding the best solution also can be referred to as the objective function or the target to be achieved for any particular problem. The common engineering objective functions involve the minimisation of operational and capital costs, the minimisation of the weight of a component, or in the maximisation of annual return (profit). Most objective functions are driven by the nature of the specific problem (Bertram, 2003). Thus, for most engineering problems, the selection of objective functions is seen as being fairly straightforward. However there are cases where the chosen criteria conflict with each other. Therefore, it is crucial to select or formulate the right objective function and the success of any decision making technique is clearly dependent on it.

In other situations where multiple criteria must be simultaneously considered, e.g., in maximising the quantity of goods delivered per year within a limited budget, for example, two conditions need to be accomplished; (1) the speed of the vessel must be maximised as far as possible and (2) the operational cost per year must be minimised. This kind of problem requires a multi-objective decision making technique, which will be explained in detail later in this thesis.

The application of decision making techniques to ship design is not a new thing; it was started as early as the mid 1960's when Murphy tried to solve ship design problems by using a single objective decision making technique (Murphy et al., 1965). This type of technique was common in ship design up to the 1990's. During that period, researchers concentrated more on General and Bulk carriers due to the large numbers being designed. Later, tankers were included in the investigations (Nowacki, 2003) along with Passenger/Car ferries (Papanikolaou et al., 1991), High Speed Craft (Jastrzebski and Sekulski, 2005) and other types of carriers. All of these researchers used the Mathematical Programming Technique approach in which the objective function was cost or profit. In fact, this approach has been a frequent feature of ship design for many years.

More recently, a single objective decision making technique was combined with Stochastic Process Techniques and Statistical Methods in order to handle multi-objective decision making techniques more efficiently. This combined approach is normally known as a Hybrid or Integrated Approach (Cui and Turan, 2009; Dimopoulos and Frangopoulos, 2008). As multi-objective decision making requires a significant amount of data to be analysed, the use of an advance Mathematical Programming Technique such as Artificial Neural Networks (ANN) can be beneficial. The large amount of data produced from the simulation process gives good indications that the study has taken all possible conditions into account in order to provide the information to solve the given problems. However, this volume of data can easily be overlooked, misinterpreted and mistakes can be difficult to identify. However, an ANN is able to handle these problems efficiently and effectively.

Ship design problems involving multiple objectives have been discussed by Sen (Sen and Yang, 1998; Sen, 1992);he described algorithms able to apply multiple objective decision making techniques to deal with large engineering design problems in general and particularly with application to ship design problems.

This study looks at the design of the overall arrangement an LNG carrier in the preliminary stage. LNG carriers are amongst the most complex of vessels designed by engineers. The design complexity results from the interrelationships between advanced technology components, which are required due to the nature of the cargo. Before looking further at the LNG carrier components, it is necessary to understand the background of this type of vessel.

1.3. LNG Carrier: Background

The idea of transporting natural gas in a liquid state was first patented in May 1915 by Godfrey L. Cabot. The attempt to realise this idea was re-energised in 1952 by Willard L. Morrison, followed by J. J. Henry in 1954 when they developed the Liquefied Methane Barges (Ffooks, 1993). However the idea of transporting liquid gas became a reality with the first LNG carrier, named Suehiro Maru No. 8, with 150 m^3 of LNG capacity, operated from 1962 until 1983 using an internal combustion engine as the prime mover. The first steam turbine LNG vessel, the Methane Princess was the world's second LNG carrier, operating from 1964 until 1998 with an LNG capacity of 27,400 m^3 (MAN, 2009). Since then the numbers, configurations and sizes of LNG carriers have continued to increase.

An LNG carrier, as the name implies, is used to transport Liquefied natural gas across the globe. Because of the nature of LNG, which exists at a cryogenic temperature (-160^{o}C), the design and construction of this type of vessel becomes very complicated. In addition, each major component of an LNG carrier is interrelated with the others, thus increasing the complexity of construction of the ship. Assuming that a similar containment system is used, as the size of the ship increases, the amount of boil-off gas (BOG) produced will also increase. BOG needs removal in order to prevent pressure build-up in the tanks. It can be used as propulsion fuel or it can be turned back into the liquefied state and returned to the tank to maintain the level of fill. This latter option requires additional power and size of the reliquefaction plant in order to manage the volume of BOG produced. At the same time, adequate propulsion power is required to overcome the total hydrodynamic and wave resistance produced by changes in the hull shape and wetted external surface area.

Most of the LNG carrier major components (e.g. tanks, reliquefaction plants, and propulsion machineries) are manufactured by different companies, and as such, their individual performances are independently assessed. In new designs for LNG carriers, this creates a variety of options for ship-owners to choose from. However it also introduced new challenges to them in terms of selecting the right combination of components for their vessels to meet contractual agreements, for instance, the volume of LNG carried per year and the distance travelled between terminals. Thus it requires a methodology which enables the ship-owners to select the optimal combination based on cost of the components for a given task. At the same time, this tool should be able to determine the minimum numbers of a given size and type of ship for a fleet, the overall costs, and the emission pollutant products released to the atmosphere, based on the particular combination of the ship system components suggested.

A decision making technique is an analytical tool that could be employed to give the optimal system component combination needed. However this tool can only be used when there is sufficient response and behavioural data available to be processed. Such data, however, can be generated by complex simulation programs which consider the behaviour and interactions of all the inter-related components. The data must consider all the possible combinations of components, within specified limitations for each component, to ensure that the results that are produced are logical and economically sound for a given criterion or set of criteria.

1.4. Aims and Objectives

This thesis aims to develop a holistic design methodology which can produce the optimum combination of components for an LNG carrier that meets the specific transport route requirements, during the preliminary design stage. The development of this methodology would help ship-owners to select the right combination of components for an LNG carrier, to rationalise the overall fleet size, minimise overall costs of construction and operation, and to control the total mass of pollutant emission products. This methodology is thus also very useful to shipbuilders, engineers and students in marine engineering courses to understand the complexity of LNG carrier systems. The aim is thus based on creating a tool to support the decision making process for complex systems, such as LNG carriers, at the preliminary design stage.

This aim can be realised through the following objectives:

1. The development of an accurate overall mathematical model for an LNG carrier simulation.
2. The development of a model that is able to duplicate and assemble the simulation output data efficiently and accurately with minimum computational time.
3. Application of the developed tools as a decision making technique in order to achieve the optimal combination of components for given targets.

1.5. Outline of the Thesis

The study involves the development, implementation, execution and analysis of the overall preliminary design for an LNG carrier. To address this, the thesis is organised into six chapters.

Chapter one presents an introduction to the thesis with specific emphasis on the rationale, aims and specific objectives of the study. A brief layout of the thesis in achieving these objectives is also presented in this chapter.

Chapter Two presents a literature review of LNG carrier transportation development, which gives an overview of the various shipboard systems and of the alternative components that are associated with it. The review also assesses the potential gaps in the preliminary design stage process and identifies the opportunities to be undertaken in the scope of the study.

Chapter Three looks at the preliminary design process in greater detail. It explains the relationship between the principal components and observes the reaction of the results as the parameters are varied.

Chapter Four explains the development of the basic analytical tools which are a combination of the simulation method and an artificial neural network (ANN), how they work and what kind of solution will be achieved from their use.

In Chapter Five, a series of case studies are investigated to find the most suitable combinations of LNG carrier components that give the overall optimal solution for a given target, based on the proposed decision support technique.

The last Chapter offers the conclusions from this work and highlights some of the assumptions and limitations taken and proposes suggestions for future study and development in order to produce a more effective and accurate analytical methodology.

2. LNG Transportation Systems - Review of Literature

Objective

The overall aim of this chapter is to review the principal aspects of LNG transportation systems, particularly as discussed in recent technical publications.

The specific objectives of this chapter are thus as follows:

- To investigate the ways to transport natural gas,
- To study each of the main components of an LNG carrier, and
- To identify the design and evaluation gaps in this field.

2.1. Introduction

An LNG carrier is a special single-purpose vessel that has been developed and designed to transport natural gas by sea, worldwide, in a saturated, very low temperature condition, at atmospheric pressure and not requiring a pressure tank (Oka et al., 2004). LNG carriers are the most expensive, complex and potentially hazardous cargo carriers that are operating across the world’s oceans (ABS, 2003). The LNG is stored inside thermal containment systems in which it is essentially kept from boiling at its saturated temperature throughout the voyage. The penetration of external ambient heat from the surrounding air and sea to the cargo through its containment system, together with the effects of mechanical accelerations resulting from the ship’s six degrees of freedom motion in waves, and the general cargo operations, will stimulate the evaporation of the LNG (Ohira et al., 2002). This evaporated gas is usually referred to as Boil-off Gas (BOG). Since BOG is generated throughout the journey, continuous removal of this gas is required in order to prevent an increase in the pressure inside the cargo tank due to the increased latent heat energy. The act of removing the latent heat energy simultaneously cools down the remaining LNG.

Currently there are two common types of LNG carrier cargo tank design namely 'prismatic' and 'spherical' forms as shown in Figure 2-1 and Figure 2-2 respectively.

Source: GTT Photo library

Figure 2-1: Prismatic Type of LNG carrier

Source: Kvaerner Moss Photo library

Figure 2-2: Spherical Type of LNG carrier

2.1.1. Summary of Available LNG Transportation

Before proceeding further with the discussion of LNG carriers, it is useful to review, albeit briefly, the ways in which natural gas is transported from the producer to the consumer. Natural gas occupies a large storage volume at ambient temperatures (Watanabe et al., 2007), therefore it is advisable to transport this gas immediately after it is extracted out of the underground reservoir. There are several methods that are used to export natural gas from the drilling platforms to the importing countries. According to Thomas and Dawe (2003) these include: (1) transportation by LNG carriers, where the gas is first cooled to a liquid state at approximately -160^{o}C at atmospheric pressure, and then pumped as a fluid into well-insulated containment systems inside the ship before being transported; (2) via pipelines to transfer the natural gas in gaseous form overland or on the seabed under a pressure of between 4.8 and 7.5 MPa. This method is used extensively throughout Europe, USA, South America and the Middle East; (3) transporting it in the form of Compressed Natural Gas (CNG) where the gas is placed in a pressure vessel, or a Coselle, at high pressure (25 MPa) before being shipped to other countries; or (4) transported in the form of Natural Gas Hydrate (NGH). NGH is the product of mixing natural gas with water to form a stable crystalline ice which can be transported by bulk carriers in large ‘thermos flask’ type tanks and stored at close to adiabatic conditions.

2.1.2. A Comparison between LNG Carriers and Pipelines

The most widely used natural gas transportation methods are LNG carriers and pipelines. However, there are some issues regarding pipelines which can make transportation by sea more promising. One of the dominant issues regarding pipelines is their overall cost of construction and subsequent operation. It was estimated that the average cost of installing pipelines in 2002 was between one and five million US dollars per mile (Thomas and Dawe, 2003). However, the construction cost can dramatically increase depending on the topography over which the pipeline is laid, which may vary between mountains and the flat seabed.

The overall cost of transportation using an LNG carrier, which includes building and operating the carrier itself, plus gas liquefaction at the exporting terminal and LNG gasification at the importing terminal, can become more cost-effective if the distance between the terminals at the importing and exporting countries is above 2200 miles, which is frequently the case (Thomas and Dawe, 2003).

The other issue lies in the degree of operational flexibility in selecting the best transport route to the importer's LNG terminals. In the case of pipelines, there is no operational flexibility once the pipelines are laid down. Both export and import points are fixed until a new route for an alternative pipeline is built. The only choice for the exporter is either to allow or to shut off the supply of natural gas through the fixed pipeline. However, in the case of LNG carriers, there is the flexibility to operate over a different route as instructed by the carrier's owner, including to a different importer, with the added benefit of being able to seek shelter from natural disasters, such as a tsunami or an earthquake.

In the case of earthquakes, for example, which have been occurring more frequently of late, a pipeline will often suffer extensive damage due to its mechanical rigidity. A series of earthquakes affecting natural gas pipelines have been recorded in recent years. For example, the Coalinga in 1983, the Whittier Narrow in 1987, the Northridge in 1994 and the Chichi in 1999 (Guha and McGowan, 2008). As a result, the supply of natural gas stopped, resulting in a loss of revenue for the exporter and additional time and extra costs were incurred to repair the damaged pipelines and restore the flow.

Political disputes sometimes create another difficult problem for the operators of pipelines. The most recent example was when the Ukraine government stopped the natural gas trans-shipment supply to many countries during the winters of 2007 and 2008 due to a payment dispute between Russia and the Ukraine. Hungary, Bulgaria, Romania, Poland, Turkey and Greece suffered from this action (Landale, 2009; Reuters, 2009).

Natural and manmade issues are not limited to those mentioned above, there are also frequent terrorist attacks on pipelines (Simonoff et al., 2005). Karmon (2002) identified the motives of these attacks, which can be divided into three groups: (1) to provoke serious economic problems and create a demand for power which increases the internal instability in a region; (2) to prevent foreign countries who have interests in this commodity from investing and supporting the local government; and (3) to use profits from the sale of the stolen commodity to buy weapons to fight against either the local government or other terrorist groups.

Considering all of the advantages and disadvantages mentioned above, it is clear that the LNG carrier would be one of the more significant and attractive options to transport natural gas. Therefore, it is not surprising that the LNG sea carrier trade grew by an average of 7.7% annually compared to that for pipelines which has increased only 4.7% annually since 2000 (MER, 2008c).

2.1.3. Statistics Related to LNG Carriers

The main uses of LNG are to produce electricity and to generate heat. One of the main advantages of natural gas as a fuel is that it produces 50% less CO_2 emissions compared to other conventional fossil fuels (Shin and Lee, 2009; ENGVA, 2006; Thomas and Dawe, 2003). Methane, as the predominant component of natural gas consists of one atom of carbon with four atoms of hydrogen, which is the simplest hydrocarbon molecule. Hence, the production of carbon dioxide will be much reduced compared with the combustion of other hydrocarbons (i.e. propane, butane, etc) that have more carbon atoms. Moreover, with new technology, the combined cycle gas turbine engine has higher efficiency from burning natural gas as a fuel compared with steam turbine engines, producing electricity with lower fuel consumption (MER, 2008c). A further advantage is the recent increase in the price of crude oil, which in 2008 alone rose by more than 100 dollars per barrel (Miller, 2009a), thus making natural gas increasingly attractive as a source of energy.

The increase in demand for natural gas has enhanced the LNG market significantly (Yamawaki, 2002; Batcheler, 2000). The latest estimation of global LNG consumption revealed an increase of 29% in 2009 and 2010. The Middle East dominates the supply, providing 61% of the total LNG that is produced annually (Miller, 2009b).

The total world supply has been predicted to reach 500 million tonnes by 2020 (Marzouqi, 2008). The increase in demand has resulted in there being a substantial increase in the numbers of LNG carriers in service and under construction.

Prior to the 1980s there were only 42 LNG carriers in service; by 2002, the number had increased to 129 (Kuver et al., 2002) and in 2008 there were 291 LNG carriers in service and 98 vessels on order (LWS, 2008). In addition to the increase in the numbers of carriers, the liquid volume cargo capacity of individual new vessels has grown rapidly as well. Starting with 150 m^3 in 1962, increasing to 27,400 m^3 in 1964 (MAN, 2009), to 130,000 m^3 in the early 1980s and to 138,000 m^3 by the middle of the 1990s (SB, 2009). By the end of 2005, the maximum size grew again to 153,000 m^3 and continued increasing reaching 266,000 m^3 in 2009 (Motorship, 2009).

2.1.4. Challenges in the Expansion of LNG Supply

The rapid increase in numbers and sizes of LNG carriers is having a serious effect on finding and appointing competent and experienced crews to run the new types of machinery such as reliquefaction plants and advanced propulsion units with dual fuel firing technology (MER, 2008c).

The other related challenge is the migration of competent and experienced crew members to multinational companies which offer higher salaries and other incentives. As a result of this migration, the smaller companies are forced to employ relatively inexperienced crews, which may increase the risk of human error while handling and maintaining this advanced and hazardous cargo and the operation of complex vessels and systems. Similar problems are being faced by the shipyards, where the numbers of skilled workers are limited and which makes their salaries higher. This situation will increase the construction costs and delay the production of new carriers (MER, 2008b).

Some corrective actions have been made by the ship-owners/shipyards who are embarking on in-house training programmes to acquaint their crews/workers with the latest technology used in new-build LNG carriers. At the same time, this problem can also be solved by increasing the number of ship cadets/shipyard employees, and by educating them in the latest technologies in the marine field. This will make them competent to sail and work with this type of ship upon completion of their studies/training.

Historical data has shown that LNG carriers are a relatively safe mode for transporting this type of fuel, as their safety record illustrates as in Table 2-1.

Table 2-1: Accidents or Problems Involving LNG carriers

Year	**Ship**	**Description of Event**	**Personal Injuries**	**LNG Release**
1965	Jules Verne (now Cinderella)	Overfilling	None	Yes
1965	Methane Princess	Valve leakage	None	Yes
1971	Esso Brega (now LNG Palmaria)	Pressure increase	None	Yes
1974	Massachusetts (barge)	Valve leakage	None	Yes
1974	Methane Progress	Touched bottom	None	No
1977	LNG Delta	Valve failure	None	Yes
1977	LNG Aquarius	Overfilling	None	Yes
1979	Mostefa Ben Boulaid	Valve leakage	None	Yes
1979	Pollenger (now Hoegh Galleon)	Valve leakage	None	Yes
1979	El Paso Paul Keyser	Stranded	None	No
1980	LNG Libra	Shaft moved against rudder	None	No
1980	LNG Taurus	Stranded	None	No
1985	Gadinia (now Bebatik)	Steering gear failed	None	No
1985	Isabella	Valve failed	None	Yes
1989	Tellier	Broke moorings	None	Yes
1990	BachirChihani	Hull fatigue	None	No
1996	LNG Portovenere	Fire-fighting system malfunction	**6 dead**	No
2002	Norman Lady	Collision with submarine	None	No
2003	Century	Engine breakdown	None	No
2003	Hoegh Galleon	Engine breakdown	None	No
2004	Tenaga Lima	Damage to stern seal	None	No
2004	British Trader	Fire in transformer	None	No
2005	Laieta	Engine breakdown	None	No
2005	LNG Edo	Gearbox vibration	None	No
2005	Methane Kari Elin	Leaks in cargo tanks	None	No
2006	Catalunya Spirit	Damaged insulation	None	No

Source: (MBS, 2007)

There has been only one accident with fatalities over the period from 1965 to 2006 (MBS, 2007). Most of the accidents were due to human error rather than as a result of systems failure. Some of the accidents and problems detailed in Table 2-1 were clearly unrelated to the cargo role of the vessel and were of a general ship nature, e.g. grounding, fatigue and main machinery problems. The International Maritime Organisation (IMO) has created a set of rules and regulations which need to be followed while constructing and operating LNG carriers. This set of rules and regulations are known as 'The International Code for the Construction and Equipment of Ships carrying Liquefied Gases in Bulk 1993' (IGC, 1993). The code must be adopted by all shipbuilders and ship-owners who are involved in transporting liquefied gas by sea. The code is also included in the Safety of Life at Sea (SOLAS).

Carbon dioxide, sulphur oxide and nitrogen oxide are the three major contributors to the overall emission pollutants generated by ships that use heavy fuel oils as the medium to produce power. These pollution emission products are a global problem and are a contributory cause of global warming. Thus there is a clear incentive to minimise them when and wherever possible.

Shipping is a relatively low cost means of mass transportation, particularly for transporting bulk material and it is reliable and can reduce road and rail traffic. However, this industry also has the potential, if unchecked, to produce 50% of the world's air pollution by 2020, if no corrective action is taken (MER, 2008a). The political issue of pollutant gas emission in the shipping industry is addressed by international laws such as the Sulphur Emission Control Area (SECA) regulations. Possible solutions to reduce CO_2 were discussed at the United Nations Climate Change Conference 2009 in Copenhagen. Sulphur Oxides (SO_x) must be reduced from 4.5% to 1.5% by mass released to atmosphere as mandated by the SECA rules from March 2010 and the IMO has proposed that by January 2011 all new engines are only allowed to produce NO_x at levels that are 15-22% according to g/kWh below the current IMO limit (MER, 2008a; Brown, 2007). Details of the SECA regulations will be explained in subchapter 5.3.

Transporting natural gas using LNG carriers has significant advantages compared to pipelines; however, it requires dedicated engineering knowledge and technical expertise on each vessel in order to reduce the risks of failure especially when handling and monitoring the hazardous and sensitive cargo. It is important to understand the interactions within integrated LNG carrier systems in order to evaluate the relationships between design decisions and vessel operation. There is therefore a need to understand the behaviour of the individual components in order to then address the challenges posed by their collective integration to form the complete LNG carrier system.

2.2. Main Components of LNG Carriers

As mentioned previously, the LNG carrier is a unique type of vessel because of the need to accommodate its cargo's extreme physical characteristics. The BOG and extremely low temperatures of the LNG have created a huge challenge to shipbuilders and engineers. In order to address this challenge, it is necessary to know the characteristics of all of the main components that make an LNG carrier operate efficiently. As an LNG carrier is a complex system, it may be referred to as a 'system of systems'. The LNG carrier systems/components in this thesis refer to the containment systems, hull geometry, reliquefaction plant systems, power prediction variables, main propulsion units, and the mission profile variables.

These components can be separated into two groups which are 'physical' and 'operational' components. Some of these components consist themselves of a complete functional system which involves a collection of independent variables that interact with each other within the component's boundaries and overall system (Nowacki, 2003). LNG carrier components can only themselves perform at an optimal level if all of their constituent elements themselves operate optimally. Any change in the input variables to any component however will also affect the overall ship component. This interdependency has created complex relationships between the components. However, these problems can be solved by establishing a clear understanding of each component and in their multidirectional interrelationships with other components.

Six of the main components in LNG carriers are illustrated in Figure 2-3. Since all of these components/systems are interdependent and overlapping with each other, it is appropriate to study each component as a system individually before expanding to form the overall ship system in order to investigate their relationships.

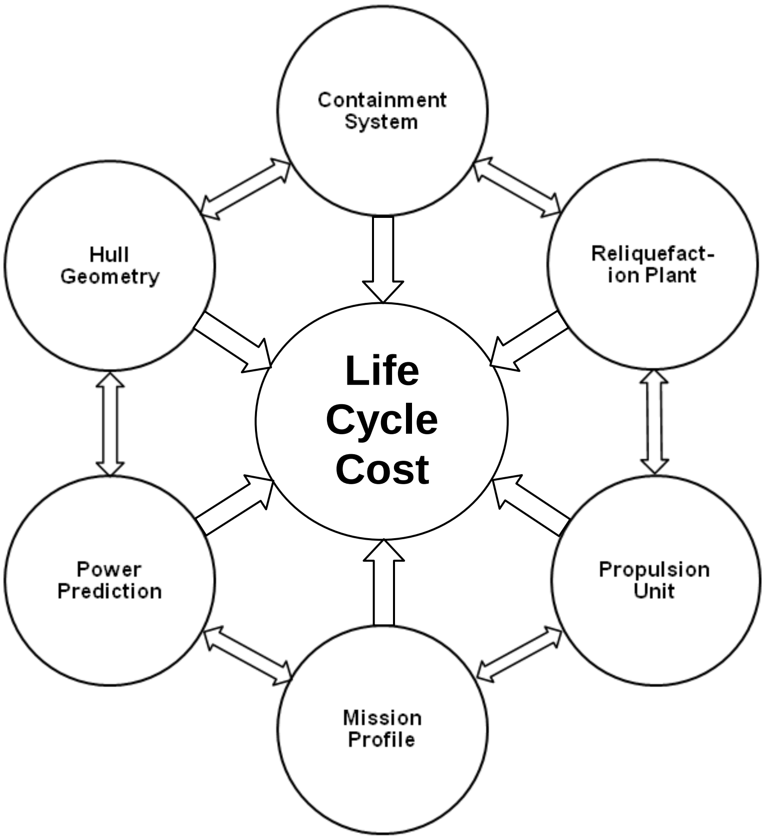


Figure 2-3: LNG carrier's Significant Components as a System of Systems.

2.2.1. Cargo Containment Systems

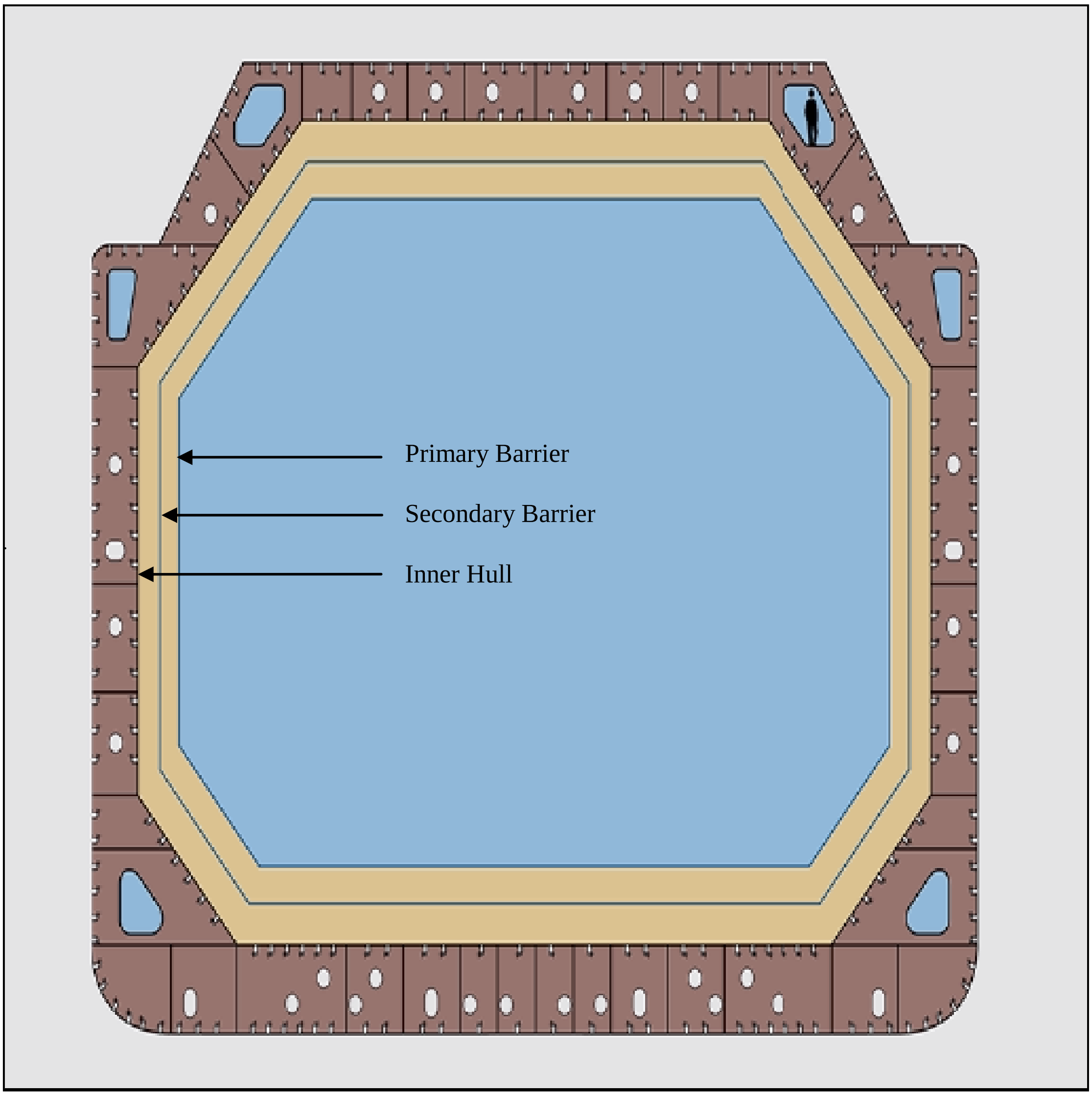
The cargo containment system is the component which makes an LNG carrier radically different from other vessels. Although this system design can be built independently, the containment system requires inputs from other components such as the hull geometry and fleet size. The design determination of the individual tank sizes can only be finalised once all of the other components of the LNG carrier have been considered.

For example, the size of the vessel is a function of fleet size for a given service which will include the volumes of LNG to be moved over a given distance for a given period of time, which in turn relate to mission profile, power prediction, propulsion units and hull geometry. The amount of BOG produced over a given period of time is an additional factor to be considered because it affects the reliquefaction plant size and its particular power requirements, and also the vessel propulsion units which may involve utilisation of some fraction of the BOG as a fuel when necessary.

A containment system consists of a primary barrier (the shape of this barrier and tank, is discussed later) to physically and securely contain the LNG liquid, a secondary barrier to provide a failsafe retaining wall in case of a leakage through the primary barrier, and a series of layers of insulation materials sandwiched between the two barriers and the hull structure (Deybach and Gavory, 2008). The primary barrier, which depends on the type of tank, is made of materials that have the ability to structurally function and withstand the cryogenic temperature due to direct contact with the cargo.

Generally 36% nickel steel (INVAR), stainless steel or aluminium alloys are the common materials that are used for the primary barrier. The secondary barrier is usually made from INVAR or a thin aluminium sheet between two layers of Reinforced Polyurethane Foam (RPUF) plus resin (referred to as Triplex). The second barrier, which is also fluid tight, acts as a hull temperature protection layer against any possible leakage of LNG through the primary barrier in the case of a membrane flaw, crack or an accident (Liddle, 2007; Yuasa et al., 2001). An illustration of the barriers and insulation is shown in Figure 2-4.

The vessel's hull structure, made from conventional steels, needs to be protected against the extreme cold of the LNG because of the potential for very severe embitterment and thermal gradient induced stresses. The insulation materials in the containment system have a low thermal conductivity coefficient in order to act as an efficient insulator to limit the external heat penetrating into the cargo hold. Limiting the heat flow into a cargo hold is very important in reducing the amount of BOG produced and it can be done by covering the whole external surface of the LNG tanks with the aforementioned insulation materials of sufficient quality and thickness. Before selecting insulation materials for optimisation purposes, additional information regarding time-related changes in physical characteristics such as aging, creep, water absorption and flammability must be considered (Adorjan, 1991).



Source: GTT Photo library

Figure 2-4: Barriers and Insulation Layers of a Containment System

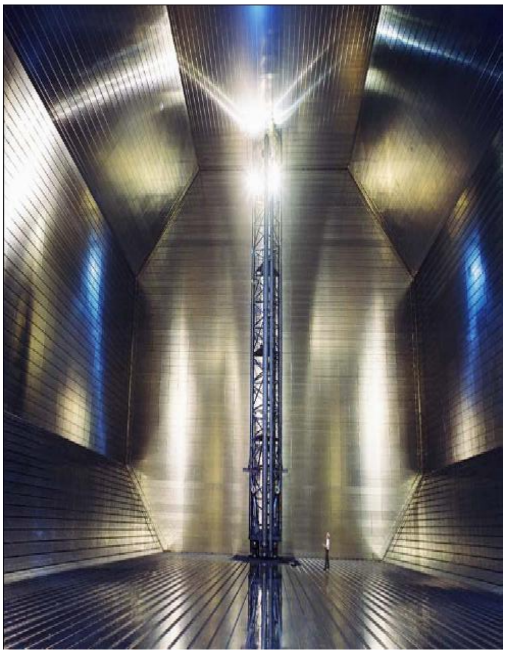
Another aspect which requires attention in selecting materials for containment systems, both the two barriers and the insulation materials, is their mechanical ability which is required to support the structure against both cargo and its own weight; this is in addition to the free surface ship-induced motions of the LNG inside the tank and which is referred to as ‘sloshing’ (Ogiwara et al., 1990).

Sloshing depends on the shape and size of the tank, filling levels, loading conditions and sea keeping characteristics (Deybach and Gavory, 2008; Liddle, 2007; DNV, 2003). The repeated impact forces from sloshing can cause fatigue failure which results in cracks in insulation panels. Several studies have been carried out to investigate and understand this dynamic failure of containment systems as well as other failure modes, particularly in the compression of insulation panels as examined during drop tests. Kim et al. (2006) used fibre optic sensors while Lee et al. (2006) applied both finite element analysis and experimental approaches in their investigations.

The IGC classifies containment systems into five types, essentially based on their structural form and load carrying capability, which are: membrane tanks, semi-membrane tanks, and types A, B, and C independent tanks. However, most of the recently built LNG carriers fall into two types, namely: membrane tanks and independent type B tanks. Each type can further be divided into two principal design models. Membrane tanks are manufactured either by the 'Gaz Transport' company, called No96 tanks, or by the 'Technigaz' company, whose tanks are referred to as MARK III tanks. The main differences appear to be in the materials and structural form of the primary barrier. These two French companies, however, have now been merged and have developed a combined system called CS1 (Liddle, 2007; Chapot, 2002).

Figure 2-5 shows the membrane tanks for two LNG carriers. Since the primary barrier for No96 and CS1 systems is constructed from INVAR, the appearance of these tanks is similar.

Independent type B tanks can be subdivided according to the geometric shape of the tank: Spherical B tanks and **S**elf-supporting **P**rismatic shape IMO Type **B** tanks (SPB) (DNV, 2003). Generally, prismatic tanks tend to map more closely to the conventional hull form of a double skeg with conventional transverse water-tight bulkheads and utilise the hull volume better than do spherical tanks.

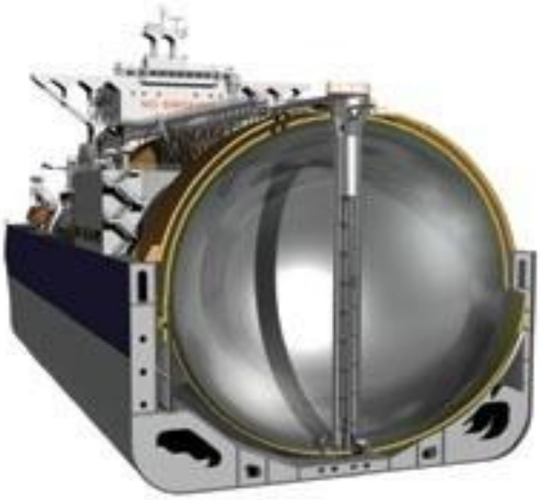


Source: GTT Photo library

No96/CS1 MARK III

Figure 2-5: Membrane Tanks

Figure 2-6 shows the independent type B tank and a spherical tank. In these tanks, weight and tank contents are fully contained by the strength of the tank structure and no forces are applied to the insulation. Similarly sloshing forces are reacted by the tank structure, not by the insulation.



Source: IHI and Moss Photo library

SPB Spherical B Tank

Figure 2-6: Independent Type B Tanks

A summary of the various LNG carrier containment systems is illustrated in Figure 2-7.

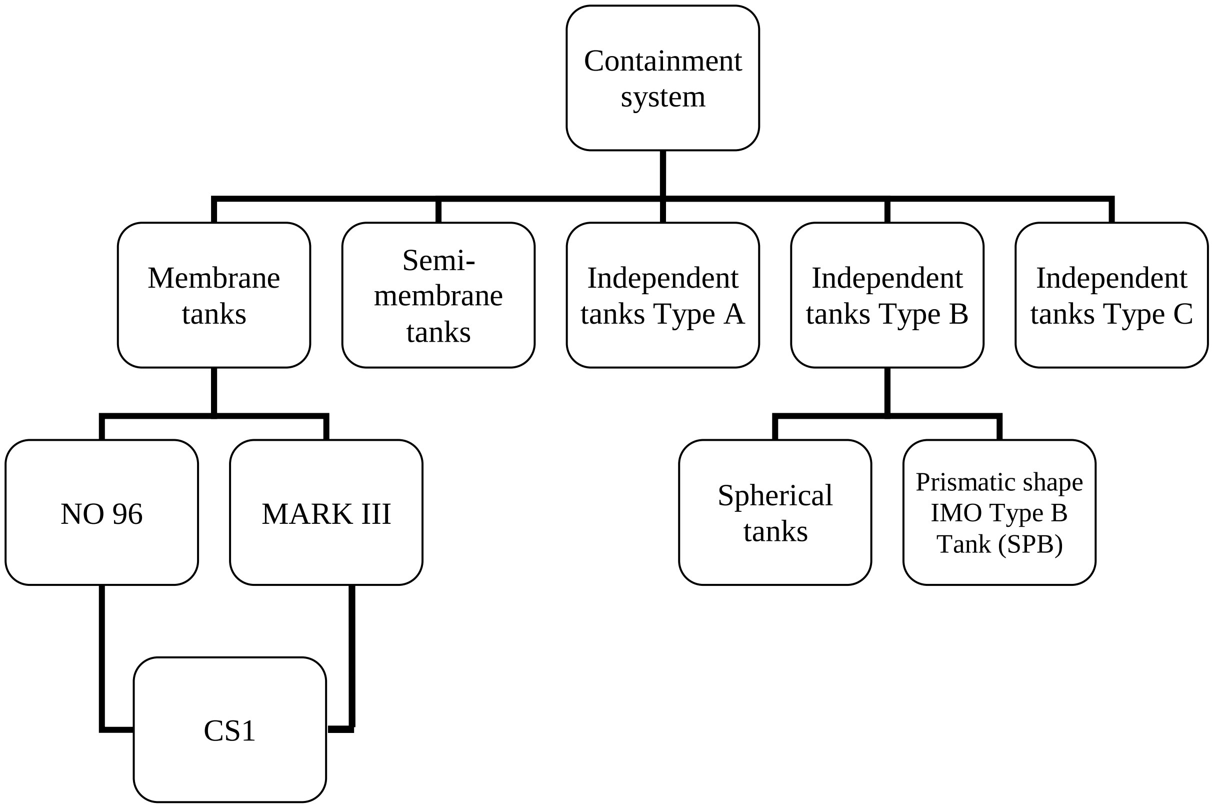


Figure 2-7: Containment System Types

Reducing costs is always one, perhaps the most important, of the financial objectives in the shipping community. With regard to containment systems, several factors have been identified which can help to reduce the overall cost of the system, although a ship-owner may accept higher capital costs as being preferable if savings can be made in operational costs. Selecting the right types of tank and types of insulation material and barrier elements, and calculating the right thickness of material based on BOG percentage targets, can reduce the capital costs and also the operational costs in terms of inspection and maintenance expenses throughout the carrier's life span. However, there are several other factors which have equal importance such as size, visibility, collision or grounding leak resistance, construction, contents-free surface effects, loading and secondary barriers (DNV, 2003).

A clearer understanding of the various aspects and consequences of each factor is achieved by making comparisons between current containment system types. Table 2-2 illustrates the main comparisons between Membrane, Spherical and Self-supporting Prismatic shape IMO Type B Tank (SPB) types.

Table 2-2: Comparisons between Containment System Types

Features	Membrane	Spherical	SPB
Size	Smaller ship principal dimensions - This tank makes more efficient use of the available cargo hold length and volume than other containment systems.	- As IGC Code and Class Rules	Smaller Ship Principal Dimensions - however the dimensions are greater than the membrane vessels of the same cargo capacity.
Visibility	Better visibility from the wheelhouse	- As IGC Code and Class Rules	Better Visibility from Wheelhouse - Same as for membrane vessels.
Collision or Grounding Response	- As IGC Code and Class Rules	Increased Safety under Collision and Grounding - The majority of the tank has larger distances from the side and bottom shell than in the other configurations.	Increased Safety under Collision and Grounding – The SPB are at a greater spacing distance than the membrane tanks but smaller than spherical.
Construction	No shipyard capital investment required in term of building workshop just to fabricate the containment systems constructed out.	Faster Construction - The tanks may be built in parallel with the ship, while the installation of the membrane tank cannot start until the construction of the holds has been completed.	Faster Construction - Same as per spherical tank vessels.
Free Surface Effects	- As IGC Code and Class Rules	Less Free Surface Effects - Due to the shape of the tank.	Less Free Surface Effects –Damping due to the presence of wash bulkheads inside the tanks.
Loading	- As IGC Code and Class Rules	Better Slack Loading and filling ratio - In general these tanks can be loaded to any level with minimum sloshing damages and due to the shape of the tank and it is possible to load the cargo at an increased filling ratio.	Better Slack Loading – With the presence of the longitudinal and transverse bulkheads to reduce sloshing.
Secondary Barrier	Complete Secondary Barrier - It can be considered an advantage from the overall safety point of view and a disadvantage from the construction cost point of view.	Possibility to Use a Partial Secondary Barrier - It can be considered a disadvantage from the construction cost point of view and an advantage from the overall safety point of view.	Possibility to Use a Partial Secondary Barrier - Same as per spherical tank vessels.

Each of the containment systems that have been reviewed above has its own merits and limitations. Since the LNG carrier main components have an interrelationship with each other, the selection of the containment system for a new vessel should not be limited to the above parameters, but must consider other components. For example, the specific dimensions of a containment system can only be obtained from the selection of the carrier size which is directly related to the fleet size. Meanwhile, additional information is required from the transportation mission profiles including delivered cargo volumes per unit of time (in years, for example) and propulsion power estimations, in order to define the appropriate fleet size.

2.2.2. Hull Geometry

The hull defines the principal geometric form and character of a vessel and is the location within which the LNG containment system will be installed. Similar to the containment system, the estimation of the required hull volume and external geometry depends on many other factors and components, and this will eventually determine the size and displacement and the total resistance to motion of a ship in a seaway. At the same time, the resistance to forward motion has a direct effect on the prediction of the installed motive power required to sail at a desired continuous operational speed.

The prismatic type LNG carriers and conventional oil and products tankers require similar hull constructions particularly the double skeg arrangement. The most significant difference is in the number of cargo tanks: LNG carriers usually have four to six tanks lengthwise while tankers typically have more than ten tanks and include several longitudinal bulkheads defining tanks into crosswise as well as lengthwise spaces, the oil and products tanks actually being formed or bounded as an integral part of the hull structure. The aim of limiting the number of tanks in an LNG carrier is to make the installation of the complex containment system easier.

The second important difference is in the total weight of the cargo volume for the same cargo capacity (ABS, 2003). The density of LNG is approximately half that of oil. It is also to be noted that LNG trade involves only the ‘all tanks full’ condition, whereas, for example, product tankers may off load parts of their cargo at different ports, thus resulting in checker board loading.

The selection of material for the primary hull structure will also have an impact on the safety and cost of the life cycle of the LNG carrier. In principle, the types of steel used as hull materials in LNG carriers are similar to the types used in other general merchant vessels. However, in the case of an accidental LNG leakage, clearly a highly undesirable situation, the steel can easily become very brittle (crystallised) when in contact with the LNG (Barron, 1999). If this occurs, the steel section in contact with the LNG will develop thermal gradient induced stresses in the embrittled region, as well as normal hull stresses and will almost certainly crack in a very short time, reducing the local strength of the ship’s hull. Therefore, a special grade of marine steel must be used for LNG carrier hull construction to prolong its fracture resistance to this crystallisation embrittlement.

Several studies have been carried out recently with the aim to reduce both the manufacturing costs and the through-life costs of hull structures. Yamamoto et al. (2008), from Nippon Kaiji Kyokai (Class NK) have developed a programme called Total Life Care (TLC) to be used to optimise the planned maintenance of LNG carriers based on both Risk Assessment and Life Cycle Cost assessment procedures. TLC involves the analysis of the fatigue strength of the hull structure, the integrity of paint coatings and the maintenance and management of machinery and equipment in order to predict the optimum planned maintenance schedule for a specific vessel. According to Yamamoto et al. (2008), the assessment has produced an optimum maintenance management plan which improves the operational safety and reliability of LNG carriers.

A study by Jin et al. (2006) has revealed that large LNG carriers with a twin skeg hull form have lower fuel consumption and increased cargo capacity compared with those vessels with a more conventional single skeg hull form. This implies a higher internal volume is available within the hull, hence a higher block coefficient. The results were analysed using a Computational Fluid Dynamics (CFD) computer program and were qualified based on model tests carried out at Statens Skeppsprovnings Anstalt (SSPA) in Sweden. They also performed an economic evaluation using both Required Freight Rate (RFR) and Capital Recovery Factor (CRF) approaches. The results showed a reduction of 9 to 10% in propulsion power requirements and approximately a 3.2% reduction in RFR, while allowing a 4 to 5% increase in cargo capacity, and a 4.2% higher CRF compared with a single skeg vessel. These results will reduce operation costs in the long term. A similar study was also carried out by Kim and Lee (2005) from Daewoo Shipbuilding & Marine Engineering Co. Ltd. However, both of these studies only focused on large LNG carriers. In reality, there are effectively five classes of LNG carriers: small with a capacity of up to 90,000 m^3, small conventional with a capacity of 120,000 to 149,999 m^3, large conventional with the capacity of 150,000 to 180,000 m^3, Q-flex with a capacity of 200,000 to 220,000 m^3, and Q-max with a capacity of up to 260,000 m^3(MAN, 2009). Thus the results do not represent all classes, of LNG carriers and they also ignore the main propulsion machinery costs which contribute to capital costs. Thus, choosing between a single skeg and a twin skeg form does not depend solely on one factor but upon a comprehensive study of other components.

2.2.3. Reliquefaction Plant Systems

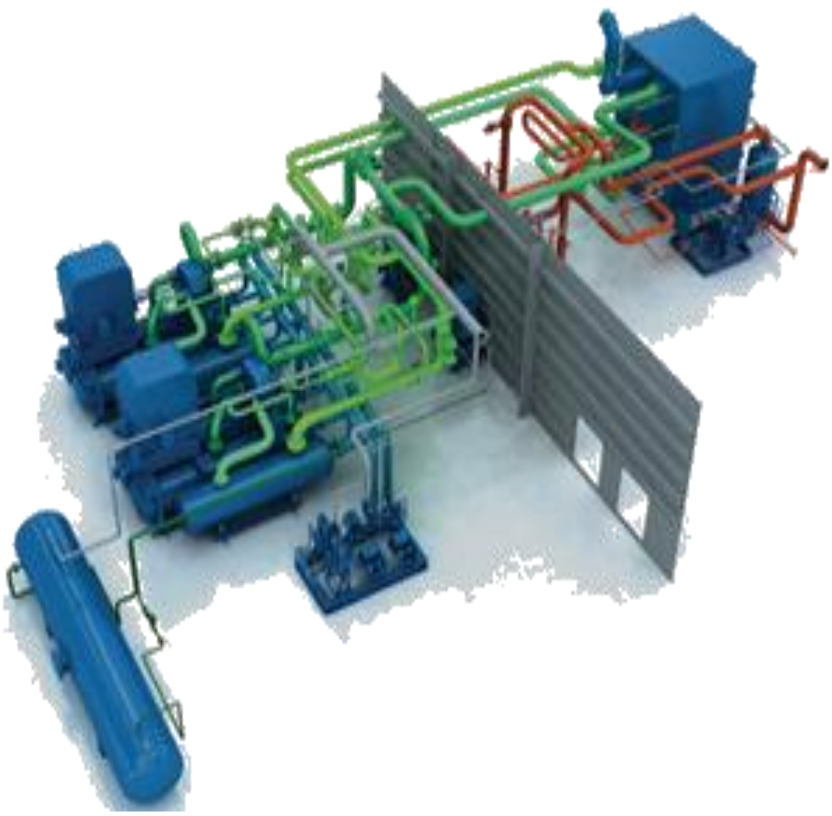
No matter how thermally efficient the cargo containment system is, the production of BOG from transported LNG cannot be avoided due to the very large difference between the external temperatures and the temperature of the LNG itself. The amount of BOG that is produced is determined by four factors, these being the exterior air and sea temperatures, the surface area of cargo tanks and the efficiency of their insulation material. The efficiency of insulators has been discussed in the cargo containment system section, thus the following section focuses on the remaining factors.

The differences between the LNG temperature inside the cargo tank and the external temperatures are clearly very high. These differences may be reduced for certain routes and sailing seasons, such as by going through colder environments, for example, sailing via the route from Norway to France in winter. In this example, the ship will produce less BOG (per day) if compared to, say, the much hotter route between Malaysia and Japan in summer. In relation to a decision making technique for the carrier design, little or nothing can be done in relation to this factor since it will not depend on the ship-owner and his choices, but much more heavily on the operator and his intended trading patterns. This leads to another factor that can be optimised in order to reduce the BOG produced: that is, the size of the cargo tank. For given cargo volume, smaller tanks mean more tanks, and larger tanks mean fewer tanks are required.

An increase in the volume of a tank will correspondingly reduce the external contact area per unit volume and the subsequent penetration of heat, which eventually reduces the amount of BOG produced. However, increases in the cargo volume in the tank will also increase the tank size which eventually increases the ship size; hence any related problems with large vessel size and/or large block coefficient such as increases in capital and operational costs need to be considered carefully.

Since the production of BOG cannot be avoided, on-board utilisation or re-processing of the BOG is necessary in order to prevent it from venting into the atmosphere, especially from the membrane tanks which cannot tolerate any increased pressure. Venting BOG to the atmosphere not only wastes its potential energy but also reduces the cargo quantity and hence value, and at the same time increases the possibility of air pollution and clearly represents a fire hazard. There are two possible options to deal with the BOG: (1) to use it as a fuel for the vessel's propulsion units, or (2) to reliquefy the BOG again and return it back to the cargo tanks.

A reliquefaction plant is a mechanical system which has the ability to convert BOG back into its liquid phase. The process of this system can be explained in terms of a thermodynamic cycle. Several alternative refrigeration cycles can be adapted for this purpose (Barclay et al., 2007; ENGVA, 2006; Adorjan, 1991), among them are the Linde-Hampson, Claude, and Reverse Brayton cycles. The Reverse Brayton cycle is the one that has been mainly selected for onboard reliquefaction systems because it is less sensitive to feed gas concentration. This cycle can be used with variable BOG production rates (this can be expected during a voyage and possibly during shorter time periods) and can perform at lower pressures of about 1.14 MPa, compared to, for example, the Linde-Hampson system which performs at 20 MPa and the Claude system which performs at 4.5 MPa. The Brayton cycle, in addition, requires a series of combined heat exchangers acting as a refrigeration unit and once the BOG is condensed, it must be immediately pumped back to the cargo tanks. A typical arrangement of a reliquefaction plant is shown in Figure 2-8.



Source: Hamworthy Photo library

Figure 2-8: Typical Reliquefaction Plant Arrangement

Reliquefaction plants onboard LNG carriers can be grouped into two main categories: process usage requirements and energy utilisation sources (Mesbahi, 2007). Each of these categories can be further subdivided into two other sub-groups as illustrated in Figure 2-9.

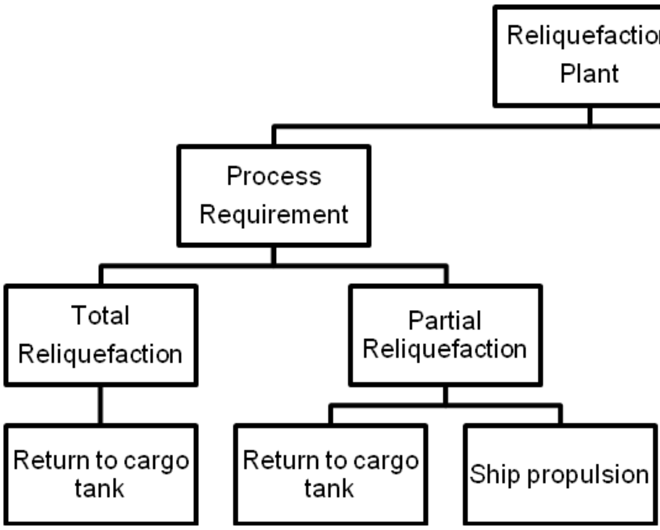


Figure 2-9: Reliquefaction Categories and BOG Management Options

The ‘Total reliquefaction’ category means that all of the BOG will be reliquefied and returned to a tank or tanks. Alternatively, in ‘partial reliquefaction’, a portion of the BOG will be used as a fuel in the vessel’s propulsion system with the rest being returned to a tank. In the ‘energy source’ category, the ‘external source’ refers to the energy which is obtained from normal bunker fuel and is required to run this system. On the other hand, ‘Self sustained reliquefaction’ refers to using a fraction of the BOG as a fuel to produce power to run the reliquefaction system itself with the rest being returned to the cargo tanks.

Total Reliquefaction can improve the annual return to the company since the total quantity of LNG will be the same throughout the journey (Moon et al., 2007). It also reduces heel and trim requirements on ballast voyages and improves the propulsion redundancy (Hamworthy, 2009). However, the initial installation cost of this system is high, estimated to be around five million US Dollars in 2002 for 138000 m^3 cargo capacity, 19.5 knots and the approximate corresponding power at the propeller is 26 MW (Kosomaa, 2002).

The use of reliquefaction plants on LNG carriers is a relatively recent development in LNG design history. The first LNG carrier with a reliquefaction plant onboard dates back to October 2000 (Ohira et al., 2002) and subsequent improvements of the reliquefaction system have continued (Sorensen and Christiansen, 2006). Mossmarine Reliquefaction made two major modifications to the basic design, the first being the optimisation of the heat transfer in the heat exchanger and which was done by introducing pre-cooling for the BOG and by installing two nitrogen expanders. The second modification was to heat the BOG before compression in addition to the use of a third stage compression with intercoolers and an after cooler. As a result, the power consumption of the system was reduced by 15-25 % from the previous levels. Sorensen and Christiansen concluded that reliquefaction plants coupled with slow speed diesel propulsion systems have shown an incremental increase in annual return of between four and five million dollars per vessel compared to the use of conventional steam turbines.

Pil et al (2006) focused on the reliability of reliquefaction systems using the time dependent Markov approach. In order to minimize the costs, three considerations were made: (1) to configure reliquefaction plants to obtain optimal redundancy, (2) to produce in-service and in-port maintenance plans, and (3) by making spare parts readily available when carrying out any repairs. Although they managed to achieve their objectives, emission of pollutants from burning fuel for power production was ignored.

Currently there are only two main manufacturers in the marine LNG reliquefaction equipment market: Hamworthy, which is licensed by Mossmarine Reliquefaction and Cryostar. Another company that has shown interest in this market is Daewoo, Shipping & Marine Engineering Co, Ltd. (Sillars, 2007). Each of these companies uses similar methods but they design to different working pressures in both the BOG and the nitrogen cycles. Selection of the most suitable manufacturing company for a new vessel's plant should not be solely based on the offers given by the manufacturers, but also on consideration of the quantity of BOG to be condensed in a given period of time and based on the type of containment system selected.

2.2.4. Propulsion Power Requirement Prediction

Propulsion power prediction is the method used for estimating the required continuous power output from the main propulsion system (as delivered by the propeller (s)), as determined by the mission profile and the design specification for the vessel (Woud and Stapersma, 2002). Two factors will determine the installed power that is required: namely the normal sailing speed and the total resistance to motion of the ship through the water.

Speed is an important parameter in determining the power requirement for a vessel. Usually, the owner specifies the normal operating/cruising speed required of the vessel and the designer ensures that the installed engine allowing for propeller and transmission efficiencies, will achieve this speed. According to Bertram (2003), the economic efficiency of the vessel can be determined by selecting the required continuous service speed because if the vessel travels at an unnecessarily high speed, the fuel consumption over a voyage will also increase considerably; however, this will shorten the time of the journey. Buxton (1976) indicated that there are several factors to be considered for the vessel to cruise at a high speed which include: efficient propulsion system, high value cargo, high freight rates and an improved hull form design.

The second major parameter that is used for power prediction methods is in the calculation of the total hydrodynamic resistance of a ship travelling in a seaway. According to Nabergoj and Orsic (2007), this resistance can be categorised into three components: motion resistance through still water, wind resistance, and added wave resistance. Arribas (2007) mentioned that any calculations that are carried out in calm water require an additional power component of 15-30 % to be added to the main propulsion system calculations in order to overcome the effect of the wave environment on ship behaviour.

This additional power is often referred to as the sea margin or weather margin. There are basically two approaches to calculate the ship's resistance: (1) using a regression analysis of random model experiments to predict full scale data (Holtrop and Mennen, 1982), and (2) numerical calculations (Arribas, 2007). Once the value of the total resistance of a ship is obtained, the power prediction can be calculated by multiplying the value of the total resistance coefficient by the speed of the ship.

Accurate estimation of the power required will prevent unnecessary loss of time and extra cost in modifying a propulsion system that is found to be either under or over powered. In addition, a major contribution to the operational costs is the fuel consumption which is a function of the selected propulsion system. The accuracy of the predicted power depends on many factors, such as ship hull form and dimensions, construction of hull form and the ship's mission profile. The results from this prediction will be used to select the required size and type of propulsion unit when all the factors mentioned above have been considered properly.

2.2.5. Propulsion Machinery Systems

As mentioned previously, the size of new LNG carriers has increased considerably in recent years and this requires more power to propel the ship. To solve this problem, the trend has been to select a propulsion unit with a superior thermal efficiency (MER, 2008c), and calculating the power required correctly, which has high interdependency with the ship's speed and the total hull resistance. This total resistance is related to the size and shape of the vessel which interconnects with all the major components of the LNG carrier. As a result, in order to select the propulsion system, one must have a holistic view of the ship rather than focusing only on certain aspects.

The steam turbine has been proven to be suitable for the prime mover of an LNG carriers since 1964 (MAN, 2009). However, based on the new construction LNG carrier orders as of October 2008, out of 99 vessel orders, only 34 selected steam turbines, 24 were being fitted with slow speed Internal Combustion Engines and reliquefaction plants, and 41 with diesel electric propulsion systems (LWS, 2008). Up until November 2009 there were 20 carriers in service using diesel electric propulsion, 39 vessels with slow speed Internal Combustion Engines and reliquefaction plants, and 267 ships sailing with steam turbine engines (SB, 2009).

This variety of propulsive machinery has given the ship-owners the opportunity to select the most suitable propulsion system for their requirements. However, selecting the right propulsion system needs careful consideration because it affects the entire LNG carrier system. The selection should focus on safety, economics, operational convenience and utilisation of BOG (Chang et al., 2008). Once this machinery has been installed in the ship, or indeed firmly defined in the final stages of design for production, it is clearly difficult to change. Changes not only demand a large amount of money but also require significant modifications to the engine room and transmission which is impractical in LNG carriers as a result of its high degree of interdependency with other components in the overall system.

- **Steam turbines**

Steam turbine propulsion systems have fewer moving parts, generally lower maintenance requirements and the usage of lubrication oil is comparatively low compared to an internal combustion engine (ICE) and gas turbine systems. However, according to Shin and Lee (2009), steam turbines have a low thermal efficiency of about 30% and this will increase the operational costs due to higher fuel consumption compared with similar vessels with higher thermal efficiency propulsion systems. In addition, steam turbines require a large volume of engine room space in order to accommodate two large boilers and this reduces the amount of cargo capacity when compared with a similar hull size carrier using other types of propulsion units. Steam turbine vessels also require specifically trained personnel to handle them (Makris, 2006).

- **Internal Combustion Engine (ICE)**

Since higher thermal efficiency has been highlighted as one of the principal aspects required to reduce the operational costs of LNG carriers, engineers have developed technology able to burn BOG alongside the conventional fuel oil; known as dual fuel engines. This technology has changed the paradigm of conventional engines such as ICE. The ICE is well known to have a thermal efficiency of approximately fifty percent (Woodyard, 1999) and by incorporating dual fuel technology, this becomes one of the more significant propulsion systems for LNG carriers. The first LNG carrier using an ICE dual fuel diesel electric system was launched in 2006. Since then, the number of carriers that use this type of engine has increased dramatically to 86 at the end of 2007 (MER, 2008b). Even the largest Q-max LNG carrier, the 'Mozah' with 266,000 m^3 cargo capacity has selected this type of engine for its propulsion system (MER, 2008c).

An additional advantage of using an ICE is that it has a lower environmental impact with reduced NO_x and SO_x emissions and provides smokeless operation (Thijssen, 2006; Kosomaa, 2002; Sekula, 2002). NO_x emissions can be further reduced by using water injection and selective catalytic reduction, while SO_x emissions can be reduced by the use of low sulphur fuel or by installing a desulphurisation plant (scrubber) on board the vessel (MER, 2008a; Brown, 2007; Kremser, 2007). However, an ICE is not free from drawbacks, such as using large amounts of lubrication oil and requiring high levels of maintenance work as a result of the large number of moving parts involved in producing the power. These moving parts increase the probability of wear and tear on the engine parts and also produce vibrations and noise which can potentially increase the risk of fatigue failure of machinery and of the local ship structure over a period of time (Kosomaa, 2002).

- **Gas turbines**

Gas turbines are also capable of using dual fuel when fitted with an electronic controller governor. The first LNG carrier using dual fuel gas turbine engines was the 29,000 m^3 cargo capacity Gas Turbine Ship (GTS) Lucian in 1974 (Mensonides, 2006). Gas turbines may be attractive because of their size which is generally small and compact. This will reduce the engine room volume and could increase the cargo capacity within a given hull (Lee and Michalski, 2002). According to Puntis (2002) this form of propulsion generally has a 42% thermal efficiency, which is higher than that of steam turbines and nearly equal to that of an ICE. Nevertheless, this type of engine has some disadvantages such as higher capital cost, the use of more expensive fuel, such as marine diesel compared to common heavy fuel, and also requires specialised personnel (Makris, 2006). The two main suppliers in this field are Rolls Royce which produce the MT30 system and General Electric (GE) Transportation with its LM2500 series (MR&AM, 2005b). Research to improve their thermal efficiency has continued in recent years and one of the ideas that is currently being pursued is that of the recovery of the normal heat loss from the gas turbine exhaust through a Heat Recovery Steam Generator (MR&AM, 2005a).

- **Electric Propulsion**

An electric propulsion system vessel entered the world-wide LNG carrier fleet in November 2006 (Castel and Sainson, 2008). This form of propulsion requires a reliable power generating system which can, for example, be achieved by having a multiplicity of diesel-electric generators. Electric propulsion for an LNG carrier may be a good idea because the generators which power the propulsion system at sea, in port can be used to run cargo pumps while the cargo is discharged. Since all propulsion engines that have been mentioned earlier are capable of turning electrical generators to provide electricity for the actual propulsion equipment, their particular advantages and disadvantages are unavoidable in their application within the actual overall propulsion system.

This integrated electric propulsion, for example, the combination of gas turbine and steam turbine usually referred to as COGES (Combine Gas Turbine Electric and Steam Turbine), has several advantages in terms of flexibility, efficiency and space reduction (Dimopoulos and Frangopoulos, 2008). On the other hand, this power system has drawbacks including its higher initial installation costs compared to other propulsion systems (Manuelle et al., 2006; Kuver et al., 2002; Lee and Michalski, 2002; Sekula, 2002).

A comparison among the alternative prime movers for LNG carriers is given in Table 2-3.

Table 2-3: Prime Mover for LNG carrier Propulsions

Prime mover	**Configuration**	**Fuel used**	**BOG**		**Transmission**	**Electric Power**
			handling	**Back Up**		
Steam Turbine	Two Boilers with HP & LP Turbines	HFO &/or Gas	Burning in Boiler	Steam Dumping	Mechanical drive through reduction gear	2 turbo-generator and 1 or 2 diesel generator
Slow speed diesel	1 or 2 slow speed diesel	HFO	Reliquefaction	Not Required	Direct drive	Usually four diesel generators
		HFO &/or Gas	Burning in the engine	Oxidizer		
Medium speed diesel	Combine HFO & dual fuel diesels	HFO, Gas or MDO	Burning in the dual fuel engines	Oxidizer	Electric drive through slow speed propulsion motor or medium speed propulsion motor and reduction gear or electric with Pod	Electric power available from main generator engines
	Dual fuel diesels	Gas or MDO	Burning in the engine	Oxidizer		
		Gas or HFO	Burning in the engine	Oxidizer		
Gas turbine	Simple cycle gas turbine usually one propulsion turbine and one auxiliary turbine	Gas or MGO	Burning in the propulsion and auxiliary turbine	Oxidizer	Electric drive through slow speed propulsion motor or medium speed propulsion motor and reduction gear or electric with Pod	Electric power available either from main gas turbine or auxiliary gas turbine. One diesel generator engines as back up.
	Combined Gas turbine and steam	Gas or MGO	Burning in the propulsion and auxiliary turbine	Oxidizer		

Source: Makris, 2006

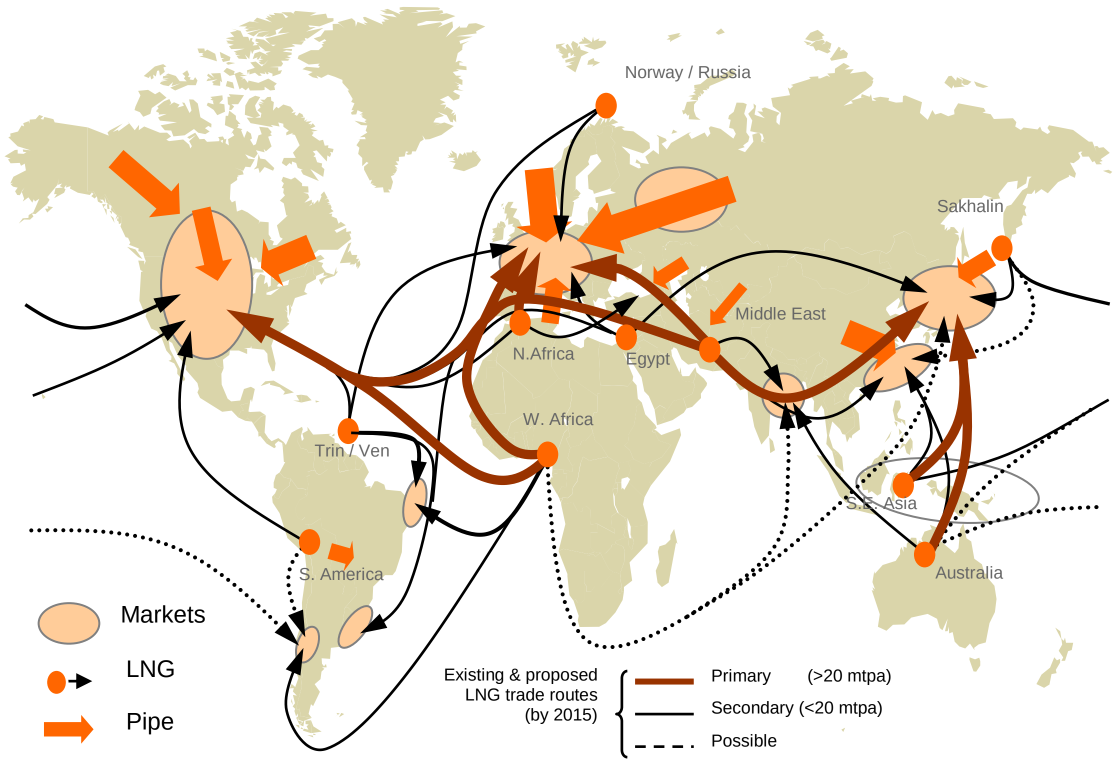
Propulsion systems for LNG carriers have experienced a number of changes over the years. These changes generally have improved the overall performance of the system, such as by having a higher thermal efficiency. Each of the various types of propulsion engines has its own advantages and limitations, thus considerations to select the most appropriate propulsion system for a new LNG carrier should not only focus on engines having a high thermal efficiency, but also on other factors including the size of the carrier which influences the total hydrodynamic resistance of a ship's hull (as mentioned in the power prediction subsection). This resistance will determine the power requirement of the carrier according to its mission profile. However, increases in power requirement eventually would result in increases both the capital and operational costs and thus reduce the annual profit returns.

2.2.6. Mission Profiles

Mission profile is clearly not a component of the LNG carrier itself but is an essential 'operational' aspect which is a virtual component of the 'system of systems' approach. The Mission Profile can be defined as the process of transferring a given amount of cargo from port A to port B within a specific time period for a given price (Veenstra and Ludema, 2006). For LNG carriers, the destination is stated in the contract and is binding between the exporter and the importer. The following are some examples of contracts between two countries:

- Contract between Trinidad & Tobago and the United States of America initiated on 4th November 1999, for the supply of 82 Billion Cubic Feet LNG per year (~2.3 Billion Cubic metres per year) over a period of 22 years.
- Contract between Nigeria and the United States of America, created on 15th June 1992, for the supply of 28 million British Thermal Units per year (~0.8 Billion Cubic meter per year) over a period of 20 years.
- Contact between the Sonatrachi Amsterdam B.V. and Trunk line LNG Company was made on 26th April 1987, for 3,300,000,000 million British Thermal Units total or 165,000,000 million British Thermal Units per year (~4.7 Billion Cubic metre per year) over 20 years (USDOE, 2009).

Clearly the numbers, size and the speed of the carriers (assuming that all are to be identical, new construction vessels) must be calculated in order to fulfil the agreement stated in the contract and to avoid potential penalty charges due to any delays in delivery of the cargo. All these parameters need to be considered holistically because they are interrelated. Additional focus on the potential operating routes is required in order to satisfy or meet existing and anticipated future international and local rules. The major current LNG routes in the world-wide natural gas market are shown in Figure 2-10.



Source: (Grant, 2009)

Figure 2-10: Natural Gas Market

In 2009, the natural gas import market was concentrated in three main areas, which were (1) Japan, Korea and China, (2) Europe and (3) America (Grant, 2009). The Middle East, South East Asia and Australia, North and West Africa, and Trinidad are the major exporters of LNG (EIA, 2009). Currently, the main trade routes are: from the Middle East to Japan, Korea, China, Europe and America; from South East Asia & Australia to Japan, Korea and China; from North & West Africa to Europe and America; and from Trinidad to America, Europe and Brazil.

Consideration of changes in the worldwide environment is clearly a significant factor for the shipping industry. The emission of exhaust gases resulting from the burning of all types of fossil fuel has produced many problems including global warming and producing acid rain. Other environmental and pollution issues related to ships include: loss of cargo due to collisions, grounding storage problems and the discharge of untreated ballast water (Veenstra and Ludema, 2006). In order to protect the natural air and sea environment, several international rules have been created, such as the definition of the SECA, e.g. the North Sea and Baltic Sulphur Emission Control Area. These regulations will affect transiting LNG carriers especially those operating from the Middle East and Africa in order to deliver LNG to North European countries.

Other constraints related to shipping mission profiles include hull size and speed restrictions when operating on specific routes, such as the Suez Canal (Perakis, 2002). All of the constraints that affect the mission profile of LNG carriers may require additional equipment, such as scrubbers to reduce the sulphur content from exhaust gases, which eventually increase the capital cost of the carrier and also affect all other ship systems and factors such as numbers of vessels required for the fleet when the physical size of the carrier is in some way restricted. It will also increase the operational costs when restricted speed regulations must be followed.

2.3. Life Cycle Costs Analysis

Life Cycle Costs (LCC) analysis is an economic evaluation technique that determines the total cost of owning and operating a product over a given period of time (Huang, 2006; Mearig et al., 1999). In this case it involves the whole life of an LNG carrier starting from the design stage through to the final scrapping of the carrier, from an economic point of view. Since all of the components in an LNG carrier contribute to all costs, they need to be grouped accordingly for a better understanding of their consequences.

Wijnolst and Wergeland (2008) have divided this method of economic evaluation study into four groups: (1) capital costs which cover the total cost of the carrier before sailing and any interest payments required to finance the ship, (2) operating costs which cover all of the necessary costs that enable the ship to sail including man power, (3) voyage costs which cover actual sailing costs such as fuel and port charges, and (4) cargo handling costs which cover costs to load and discharge the cargo. However, IOCS (2005), have included operating costs, voyage costs and cargo handling costs into fixed and variable costs categories. They defined fixed costs as those expenses that produce services but do not vary with level of volume of cargo transported, and variable costs as being those items which do vary with the volume of cargo transported.

In this thesis, the capital costs or initial expenses are all of the costs that are incurred prior to the commissioning and entry into service of the LNG carrier. Meanwhile, other fixed and variable costs, or future expenses, are all costs that are incurred after delivery of the vessel. Examples of capital, fixed and variable costs are as shown in Table 2-4.

Table 2-4: Capital, Fixed and Variable Costs for LNG carrier

Capital Costs	**Fixed & Variable Costs**
Costs of Hull	Port Costs
Costs of cargo Containment System	Total Crew Costs
Costs of Reliquefaction Plants	Cargo Capacity
Costs of Propulsion Units	Vessel Speed
Costs of Auxiliary cargo Machinery	Round Trip Distance
Overhead Costs	Days in Service/year
Taxes, fees and insurances	Days in Port/trip
Accommodation Costs	Energy Consumption/day
Percentage of Rate of Return	Costs of Energy
Economic Life	Spare Parts
	Dry Docking, Inspection & Maintenances
	Specialist Costs
	Class Society Fees

The ‘fixed and variable costs’ in this thesis are referred to as operational costs. As illustrated in Table 2-4, all main system components in an LNG carrier contribute significantly to the total sum of the LCC. In order to reduce capital and operational costs of the LNG carrier, first each of the main components has to be examined in order to reduce its own capital and operational costs through improvements in its main sub-components. Since all the ship system components are interrelated, the combination that produces lowest combined overall capital and operational cost will be selected. This target combination can be obtained with the help of decision making tools.

The relationships between the LCC and all components of a LNG carrier are shown in Figure 2-11. This figure illustrates the overview of all the components that are integrated in constructing an LNG carrier. Since the LCC for each component varies according to their purpose; three categories have been specified. They are, (1) System Life Cycle Costs, (2) Machinery Life Cycle Costs, and (3) Other Ship Life Cycle Costs. Everything related to costs within the system is placed in the System Life Cycle Costs. The major cost contributions come from the operating profile which receives instructions from the Operating Doctrine and Mission Profile.

Meanwhile, the Machinery LCC calculates all costs that involve the machinery on board the vessel. Fuel, maintenance and crew are the main costs in this category. The Other Ship LCC category will handle other costs that do not belong either to system or machinery LCC. This includes the Regulatory Body which involves taxes, fees and insurance.

It is clear that every component of an LNG carrier is interrelated to the others. Therefore any changes, regardless of the size, will contribute to costs variation. This phenomenon creates a fragile situation for the ship-owner in handling the total costs. Hence a holistic approach to select the optimum combination of the components at the preliminary stage toward the objective given is very crucial.

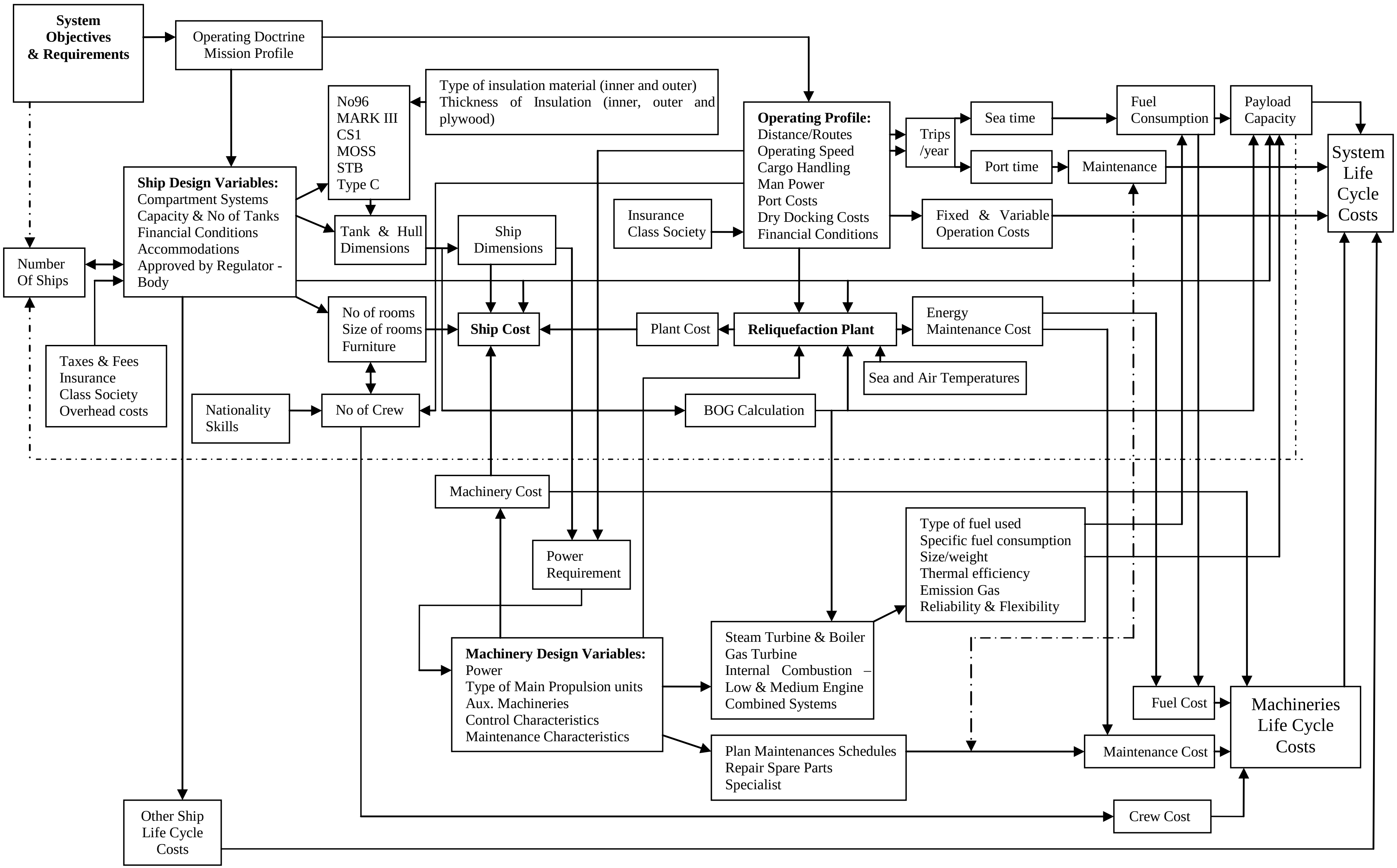


Figure 2-11: Relationship between Components of LNG carrier with Life Cycle Costs

2.4. Timeline of LNG carriers to Date

Figure 2-12 illustrates the timeline of LNG carrier development since the time of the launching of the first vessel of this type. The number of LNG carriers has increased to 355 vessels as of March 2011 in less than five decades. Over a similar period of time the liquid capacity of the new typical carrier also has increased from 150 m^3 in 1962 to 266,000 m^3 by October 2008, and it is expected to reach 300,000 m^3 in the near future (MAN, 2009). This is a result of progressive improvements in all of the main components in LNG carriers (containment system, hull geometry, reliquefaction plant, power prediction, propulsion system, and mission profile) that have taken place in parallel.

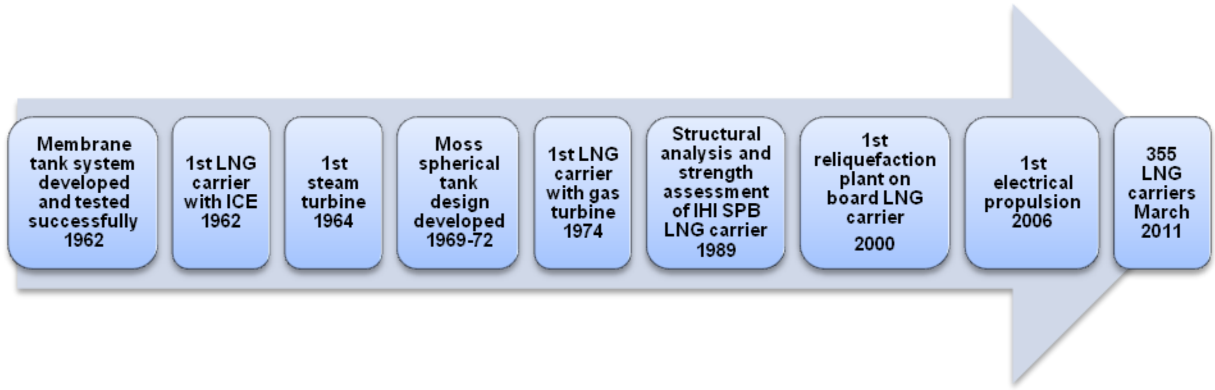


Figure 2-12: Illustration of Major LNG carrier developments

As has been mentioned throughout this chapter, each of the individual components in an LNG carrier is interrelated with the other 'system' components. There is no doubt that improving each component is important but improving one component without considering the possible consequences on other related components will not necessarily produce better results for the whole ship system, the 'system of systems'. The best way to handle this is by linking each of the components in a manner that creates a single overall system such that an improvement or modification in one component of the 'system of systems' will result in an overall improvement. The problem with attempting this approach, however, is that each of these components, individual systems, does not communicate to the others with a similar interface language which makes it challenging to link them with each other.

One possible solution to this wider problem is to transform the physical behaviour of each of the components into an equivalent numerical formula and to use these mathematical formulae as a platform for all of the components in the overall system to communicate with each other. By doing this, any changes in input variables to any one component will directly affect all related output variables simultaneously.

A ship is a complex, multifunctional system and, therefore, there are many criteria and decisions involved in selecting items in each component for a new vessel at the preliminary design stage. This is because the decisions that are made at the preliminary stage will 'lock' into the subsequent design development the eventual total costs of the vessel, thus making it an extremely important step in the overall process. From the literature review it became evident that the majority of previous studies were carried out using conventional design iterations but with no defined preliminary systems integration stage. Papanikolaou (2009) discussed methods to improve cargo carrying capacity, safety, powering and environmental issues by using genetic algorithms to perform multi-objective optimisation for ship design. However this work was at an early stage and no results were presented. A further limitation of the paper with respect to the present work was that it did not explain the selection criteria for optimum combinations of LNG carrier components.

Since each of the components in an LNG carrier are subject to a series of improvements in order to achieve given targets, most of the time the targets contradict each other thus creating further problems to be solved. Compromises between individual component performances cannot be avoided because of their interrelationships as shown in Figure 2-11. Decision making techniques will thus need to be used in order to optimise these sub-optimal components as subsystems within the overall ship system.

The use of decision making techniques at the preliminary stage of the design of LNG carriers is currently virtually non-existent, thus, this gives the author the opportunity to contribute to the body of knowledge in this area. This study is focused on the development of techniques to enable the designer to efficiently select the principle components required for LNG design at the preliminary stage.

2.5. Chapter summary

Chapter 2 has presented an overview of the LNG transportation system. Two major aspects that have been discussed in detail, the transport mechanisms for natural gas, and the main system components of an LNG carrier. The first aspect was an explanation of the methods of transporting the natural gas, their comparisons and the challenges. Basically there are many methods of transporting natural gas; however the most common are LNG carrier and pipeline. Other methods focus more on providing natural gas where LNG carriers or pipelines are not available due to economic reasons or limitations in facilities. All methods have some drawbacks but an LNG carrier offers several advantages over other transport systems for natural gas, including flexibility.

An LNG carrier is a complex system, where many subsystems are involved and overlap with each other. Thus an LNG carrier may be termed a ‘system of systems’. The main systems/components of an LNG carrier can be classified into six groups. A comprehensive discussion of the six main system components of LNG carriers is the second aspect that has been discussed in detail. The LNG carrier systems/components in this thesis refer to the containment systems, hull geometry, reliquefaction plant systems, power prediction variables, main propulsion units, and the mission profile variables. The functions, types, strengths and weaknesses of each component were explained.

As the aim of this study was to develop a decision making philosophy for LNG carriers to be used at the preliminary stage, the overall ship design process for this type of vessel needs to be understood clearly. Failure to understand the relationships between all of the principal components with the given targets of cost minimisation can jeopardise the whole idea and concept of systems integration of this thesis. The following chapter will explain the detail of the preliminary design process for LNG carriers.

3. Preliminary LNG Carrier Design Process

Objectives

The overall aim of this chapter is to evaluate the basic principles of the preliminary design process for the main components of LNG carriers.

The specific objectives of this chapter are thus as follows:

- To investigate the relationship between the LNG carrier main components,
- To study the effects of LNG carrier fleet sizing,

3.1. Introduction

The primary aim of any business is to maximise the profit for a given level of effort. This is true also for LNG transportation where any possible reduction in capital and operational costs will attract ship-owners attention. The main strategy for achieving this is to select the optimal combination of the main components of the vessel according to the given objective. There are no fixed regulations or formulae that need to be applied in choosing the right combination of components; however several techniques have been developed over the years to assist with the development process in ship design e.g. the ship design spiral. The decision making techniques for the selection of these main components need to be performed at the preliminary stage because once the main components have been selected, the overall costs will be locked-in and constrained over the ship’s life span. Modification of the selected components can be done at a later date; however it would come with a considerable cost and programme delay. The modification would not only involve buying a new component, it also requires re-arrangement of the ship’s layout in order to accommodate the new component. This therefore, requires additional capital costs which would potentially conflict with the ship-owners interests.

There are two main elements to the preliminary design stage, namely (1) technical form and arrangement design, and (2) associated cost estimation. It is hard to dispute the influence of costs on the ship-owner because they relate directly to profit. These costs can be grouped as capital and operational costs. Sometimes, components may be comparatively cheap to purchase and install. However, in order to maintain these components, an accumulative large sum of money throughout the ship's life span may be required. In order to solve this problem, the first element of the preliminary design, known as technical form and arrangement design would come into play. In terms of technical design, each main component, with their feasible alternatives, will be investigated given their advantages and limitations. Following this, a complete study should be carried out to understand the pattern of relationships between all components. By undertaking this investigation, the general directions to achieve the given cost targets can be narrowed down.

3.2. Relationship between the main components of an LNG carrier

An understanding of the relationship between all components of the LNG carrier will illustrate the sophisticated nature of this type of vessel. It would also give a rational explanation of the results, which can predict the trend of the relationships when there are changes in the selected parameters. Two main parameters have been selected for investigation, namely ship's size (which represent the amount of cargo volume) and speed as they must be selected in order to ensure the required LNG delivery schedule. Both of these parameters would produce high impacts on the other components. The results of this investigation are presented in the following sections which are based on the data collected from the holistic modelling of an LNG carrier which has been developed and will be explained in the next chapter.

3.2.1. The Effect of Overall Ship Size

As new LNG carrier designs are getting larger, it is interesting to understand the relationship between their size and the other main components of an LNG carrier. The following bullet points highlight the relevant topics that need to be investigated.

- **Relationship with the type of Containment System**

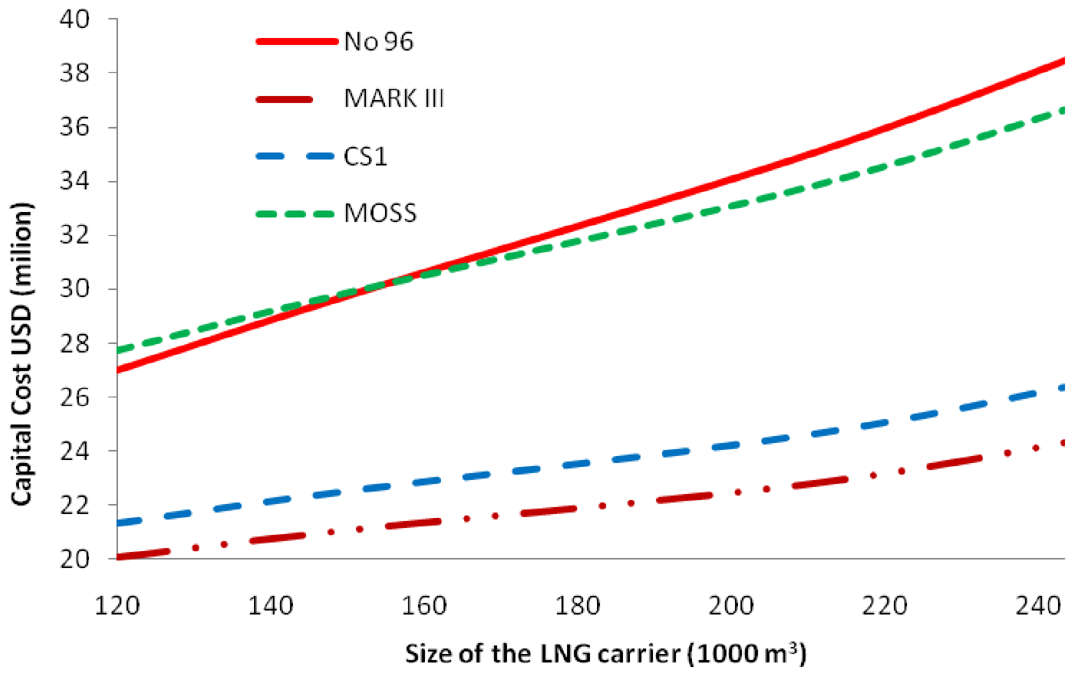


Figure 3-1: The effect of size of an LNG carrier and the type of Containment System on Capital Costs

As the size of the ship increases, the LNG tanks also get larger because they are part of the hull structure. Thus, the amount of material used to construct this containment system also increases. Since the cost of containment system is heavily dependent on the amount of the material used, the cost of this system will naturally increase. Furthermore, as the capacity and size increase, so also does the man-power required to construct and install the containment system.

A comparison of No 96, MARK III, CS1 and Moss containment systems, which are the most commonly used systems for LNG carriers, indicates that the MARK III has the lowest cost of construction. Thus this gives advantages to the MARK III compared to other containment systems for the ship-owner because it will help to minimise the vessel capital cost. The CS1 system is second, with an approximately seven percent higher cost than the MARK III. This is due to the material used for the primary barrier. The price of a square metre (m^2) of INVAR of 0.762 mm thickness was £185 as of July 2008 (Alloy, 2008) hence it is not a surprise that the cost of a containment system using INVAR as a barrier is much higher than those using other materials.

Figure 3-1 shows that as the size of the ship increases, the capital costs also grow accordingly. Although the ship-owner is always searching for possible ways to reduce the cost of the ship, selecting the MARK III as the lowest cost containment system is not necessarily the right ship system decision. For example, the MOSS type of containment produces the minimum percentage of BOG per day as illustrated in Figure 3-2. This is because the insulation materials and geometry limit the external heat penetration into the cargo tank. Thus it can be seen that careful consideration of all other parameters is a better overall system approach before making the decision on the containment system because all of the components in an LNG carrier are interrelated with each other.

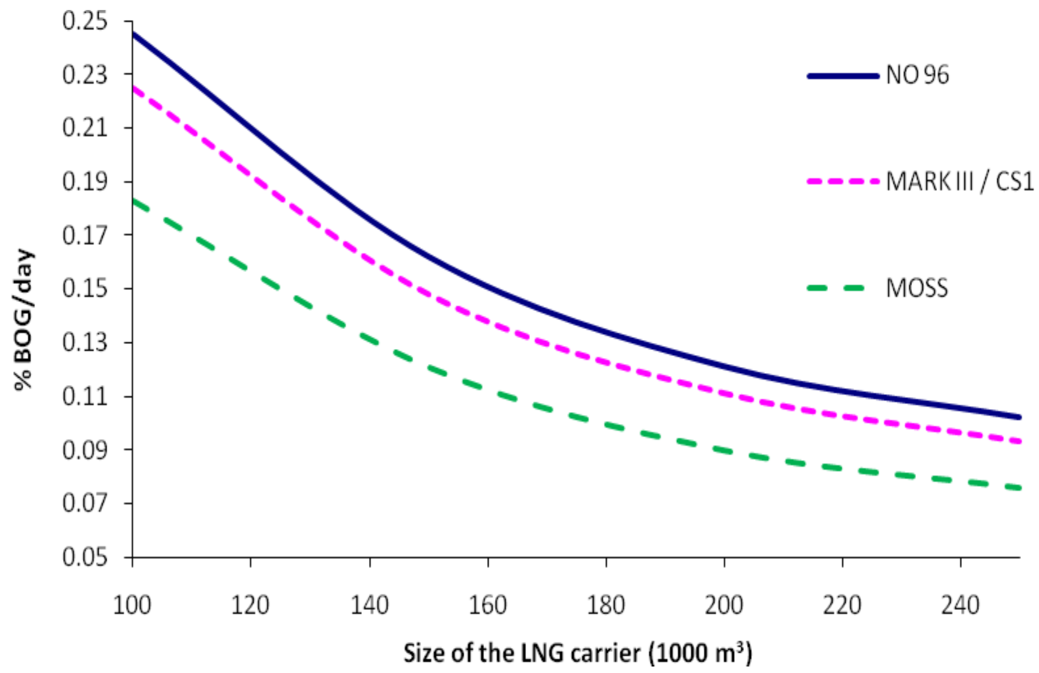


Figure 3-2: The effect of size of an LNG carrier and typical percentage of BOG per day

- **Relationship with the Reliquefaction Plant**

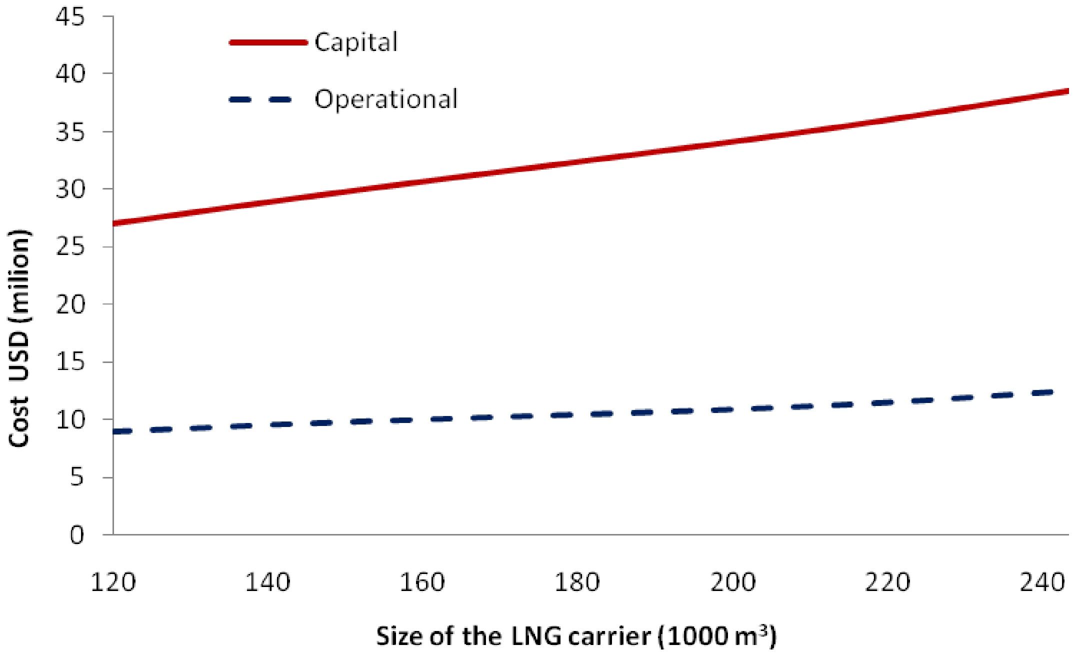


Figure 3-3: The effect of size of an LNG carrier and the Reliquefaction Plant on Cost

Figure 3-3 shows the variation of the capital and typical operational costs for the reliquefaction plant. The cost of both items increases slowly as the size of the vessel increases. The reliquefaction plant is used for the condensation of BOG, since the production of this gas cannot be eliminated as discussed in the previous chapter. As the capacity of the cargo increases, the surface area of the tanks also increases. As a result, more BOG will be generated and it is necessary to remove this from the cargo tanks, especially for membrane tanks which do not tolerate any increase in internal pressure.

Since more BOG needs to be liquefied, a larger capacity reliquefaction plant is required; hence the capital costs increases with vessel size. Moreover, the energy that would be required to perform the reliquefaction process would also increase. This energy is required to run the various pumps and compressors. The source of the energy is either electricity or steam and the costs depend on the size of the plant. If a larger plant is required, clearly more energy would be required; hence, higher operational costs are expected as indicated in Figure 3-3.

There are four principal factors that influence the production of BOG; these being the prevailing exterior air and sea temperatures, the size of the cargo tanks and the efficiency of their insulation. Two major components of LNG carrier, namely the containment system and the size of the vessel are the only parameters that can be controlled, since the exterior air and sea temperatures are uncontrollable. Since size of the vessel affects almost all of the main components of an LNG carrier, the decision to select the type of reliquefaction plant must be based on a comprehensive study of all of the components because they are interrelated.

- **Relationship with the Propulsion Units**

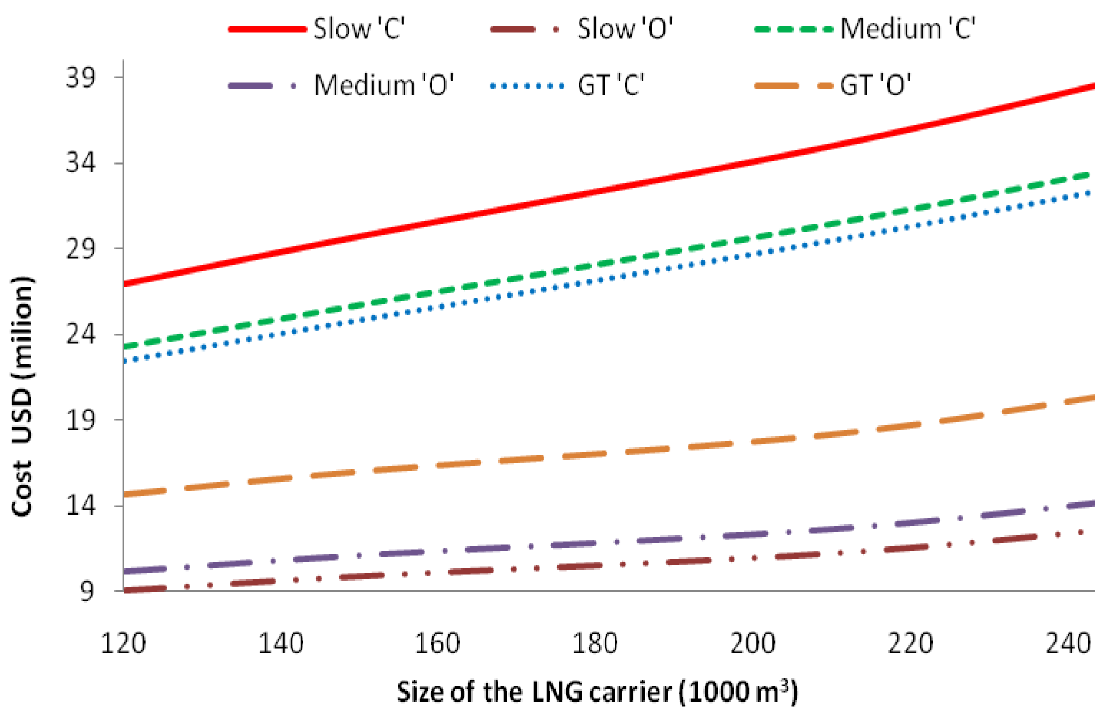


Figure 3-4: The effect of size of an LNG carrier and the Propulsion Units on Costs

Where:

Slow is a slow speed internal combustion engine,

Medium is a medium speed internal combustion engine,

GT is a gas turbine engine,

'C' is the capital cost, and

'O' is the operational cost per year.

It is clear from Figure 3-4 that as the size of the ship increases, both the capital and the operational costs also grow accordingly. The cost difference for each type of prime mover is due to the variation in engine prices, and, for example, the specific cost per kW of the slow speed engine is the highest when compared to both medium speed engines and gas turbine engines (Woud and Stapersma, 2002). Hence, the gas turbine engine may be selected by the ship-owner because it is the cheapest prime mover for an equal power requirement according to the size of the vessel. However, other factors also need to be considered, such as thermal efficiency (as mentioned in the previous chapter), because the fuel consumption will vary accordingly with it. The higher the thermal efficiency, the lower the fuel consumption for that particular prime mover however, the gas turbine engine uses marine diesel fuel, which is more expensive than heavy fuel oil, and this makes its operational costs higher compared to the other options for the same required power output. Since the life span of the typical LNG carrier is about 40 years, the cumulative total operational costs will become very significant. Thus, the selection of the propulsion units must consider all the parameters holistically.

- **Relationship with the Hull geometry**

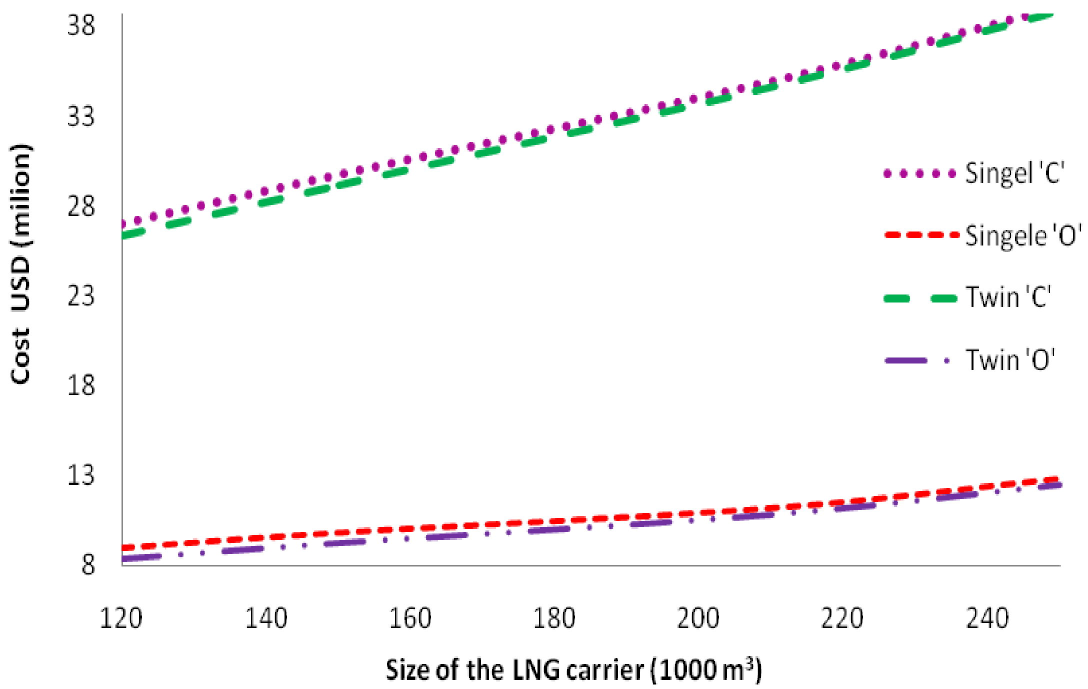


Figure 3-5: The Effect of size of an LNG carrier and the Hull Geometry on Costs

Where:

Single is a single skeg,

Twin is a twin skeg,

'C' is the capital cost, and

'O' is the operational cost.

Figure 3-5 compares the costs of an LNG carrier in single and twin skeg designs within the ship's cargo volume range of 120000 to 250000 m^3. It can be clearly seen that the costs for both single and twin skeg increase with size.

Since the size of the ship's hull is a reflection of the size of the overall containment system, increases in the ship size will increase the production of the BOG and hence it will increase the power required for the reliquefaction plant to re-liquefy this gas. Moreover, as fuel consumption is a function of the power of the engine, it will also increase. All of these factors cause the operational costs to rise.

Selection of the hull size and geometry is complicated because it involves all of the LNG carrier main components, thus any decision requires a comprehensive understanding of this complex system of systems.

- **Relationship with the Power Prediction**

The Power Prediction method is an analytical tool that is employed in order to calculate the propulsive power requirement for a new vessel based on consideration of all of the components that are related to it. There are many variables involved in this calculation; however, the main selected variables are the sailing speed and the total hydrodynamic resistance of a ship through a seaway. As the size of a vessel increases, the total resistance of a ship would also increase, hence the result from the power prediction will rise accordingly as shown in Figure 3-6.

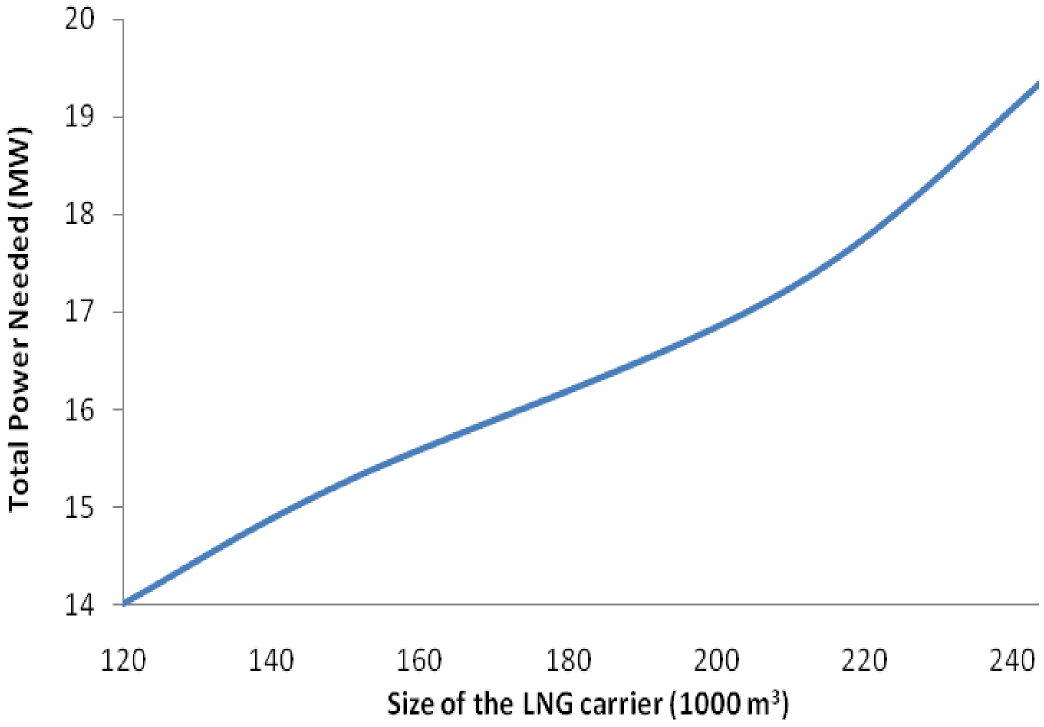


Figure 3-6: The effect of size of an LNG carrier and the total Power Requirement

Since the power prediction can be obtained by multiplying the total hull and appendage resistance by the service speed of the ship, allowing for various transmission and propeller efficiencies, the selection of the main propulsion machinery system can then be started through the main engine database, which has been developed for this study as a look-up table. Selection of the service speed of the vessel will be discussed in detail in the next bullet point. However, before selection of the main propulsion machinery can take place, all of the related components in the LNG carrier must be checked for any conflict of interest between them in order to achieve the given objectives. One possible way to resolve this conflict is by making some compromises between the various system components.

- **Relationship with the Speed**

The overall size of the ship (in terms of its required cargo carrying capacity) is another parameter that has a significant impact on costs with changing speed. The relationships between service speed and hull size for slow speed internal combustion engines (other engines having a similar pattern of graph) are shown in Figure 3-7.

It can be seen from Figure 3-7 that as the cargo capacity and overall size of the carrier increase, the engine power that is required to propel the ship according to the mission profile, specifically the service speed, also increases. This eventually increases the capital cost because the cost of the main propulsion machinery is directly proportional to the required power (Woud and Stapersma, 2002). Hence, designing for the minimum acceptable service speed of the vessel will reduce the capital cost, because it reduces the amount of power required from the main engine. However, it will require a longer time to deliver the LNG cargo. This eventually may require an additional vessel in the fleet in order to deliver the contracted volume of cargo on time. However construction of an additional vessel is not a very attractive idea because it will end up with an increase in total vessel costs.

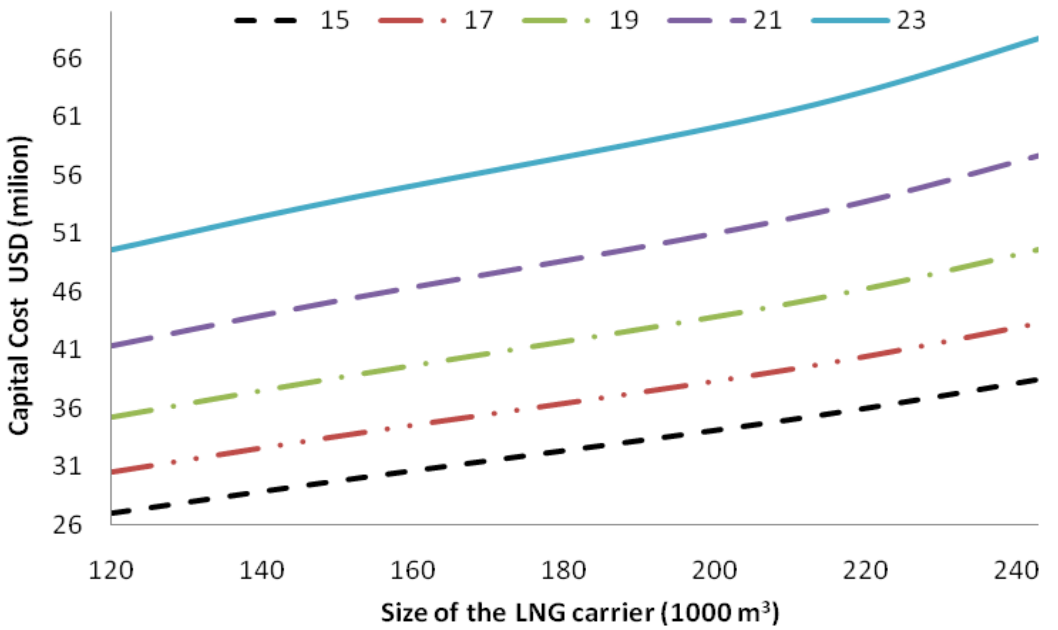


Figure 3-7: The Effect of Size of an LNG carrier and the Speed in knots on Capital costs

The ship's speed needs to be minimised, within acceptable limits, in order to reduce the capital and operational costs of the LNG carrier (a discussion on the operational costs of LNG carriers with respect to speed is given later in this chapter). However reducing the ship's speed will affect other main components of the LNG carrier, which creates a dilemma. Thus, selecting the optimal service speed must take into consideration all of the given targets.

3.2.2. The Effect of Ship Speed

Normally a ship is designed to continuously cruise at a particular speed subject to weather and sea state conditions. There are many parameters that contribute to the selection of an appropriate service speed. The following discussions will focus on these relationships. Again the following graphs have been created with the aid of the simulation program that was employed as part of this research, except for Figure 3-8.

- **Relationship with the Containment system and the Reliquefaction plant**

There is no specific relationship between the characteristics of the containment system and the service speed of the vessel. The containment system is where the LNG is stored until it is discharged at the delivery port. While transferring LNG from one port to another, BOG is generated due to either heat penetration through the insulation, or mechanical energy gain from wave induced ship motions. The total amount of BOG that is required to be re-liquefied and thus the cost in energy required is highly dependent on the number of days at sea. The rate of BOG generation per day is not uniform and will largely depend on external weather conditions which can vary. The number of days at sea can clearly be reduced by increasing the speed of the ship.

Assuming an LNG carrier with 150000 m^3 total cargo capacity is sailing from Malaysia to Japan; with the containment system managing to maintain the BOG production level at 0.15% per day. If operating at 20 knots, this vessel will reach Japan within 5 days with a total of 898 m^3 of LNG required to be condensed within this period by the reliquefaction plant. However, if the ship speed increases to 23 knots, the number of days at sea will be reduced to 3.5 days, and hence only 562 m^3 of LNG would require re-liquefying. This simple calculation is illustrated in Figure 3-8. Thus the faster the ship sails, the lower the power consumption required for the reliquefaction plant. A given reliquefaction plant can re-condense a certain amount of BOG each and every day at sea. If this matches, or slightly exceeds, the maximum daily rate of BOG production then the capital cost is unchanged with speed, and the operational cost is fixed with speed per day and thus increases in proportion to the voyage duration in days.

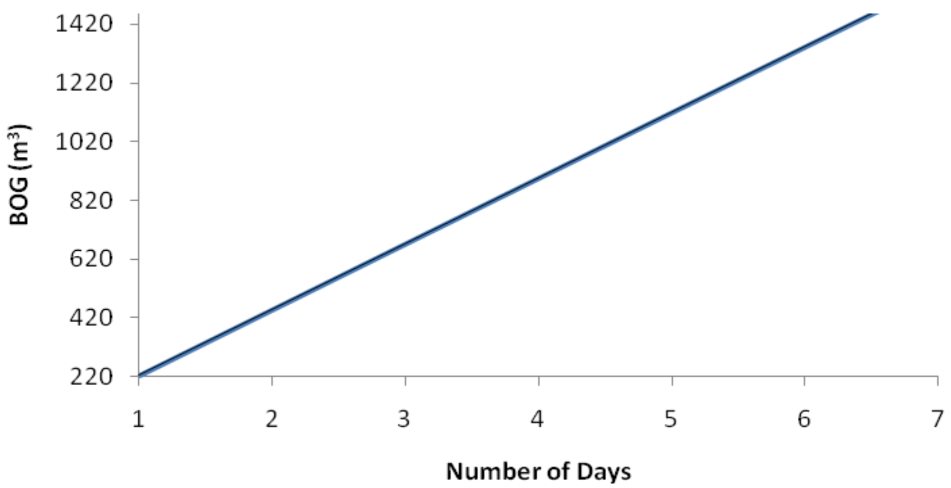


Figure 3-8: The effect of Boil-off Gas and the Number of Days

The total power calculation for the reliquefaction plant may then be translated into the cost associated with meeting the projected average daily demand. These costs are added into the overall operation costs. Since the reliquefaction plant's power consumption depends on the volume of BOG produced in a given period of time and with assumed environmental conditions, which are interrelated with the other components of the LNG carrier, the operational costs will thus vary accordingly. The actual power consumption of this plant can only be estimated when all the other main system components have been considered and selected.

- **Relationship with the Propulsion units**

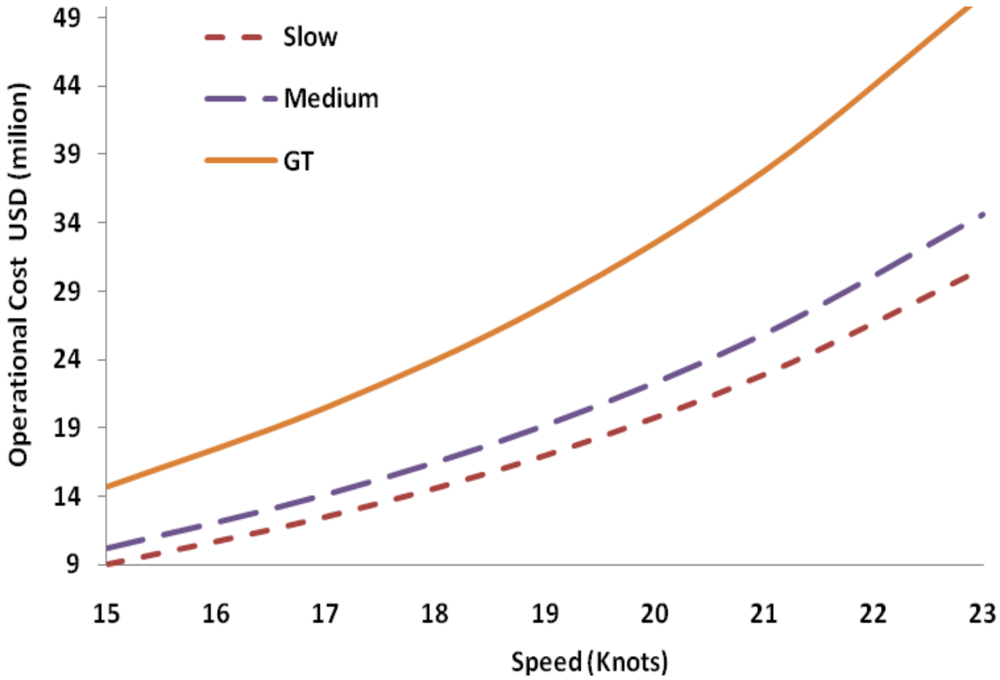


Figure 3-9: The effect of speed of an LNG carrier in knots and alternative Propulsion units on Operational costs for a given size of vessel

Where:

Slow is a slow speed internal combustion engine,

Medium is a medium speed internal combustion engine, and

GT is a gas turbine engine.

Figure 3-9 illustrates typical variations of operational cost with three types of propulsion units between 15 and 23 knots. The three prime movers that have been considered are slow and medium speed internal combustion engines, and a gas turbine engine. Although the steam turbine is one of the main engines that are used for LNG carriers, its low thermal efficiency which is less than 30% and its large space requirement for two main boilers have made this type of engine less attractive in recent years. The steam turbine is only likely to regain its popularity for LNG applications if its thermal efficiency can be increased to be similar or better than the other types of engines. This may be possible given the ongoing research and development currently being undertaken.

Overall, the dimensions and costs of all engines increase as the speed of the vessel increases. However, slow and medium speed internal combustion engines showed a more gradual increase in their operational costs than did the gas turbine engine for increasing vessel speed.

Specifically, as the speed increases, more power and thus more fuel is required and hence this increases the operational costs. Furthermore, the gas turbine uses marine diesel which is more expensive than heavy fuel oil, which makes the increase in costs even more significant. However, a gas turbine requires a relatively smaller physical space and hence engine room and therefore it can increase the amount of cargo that can be transported, which can help to justify its use as the main engine for LNG carriers of a given hull size.

Thus selecting the main propulsion machinery for an LNG carrier is not a simple task because it impacts on all the other main components. This is due to the complex relationship between the components, thus, the choice of the propulsion units for a new carrier must involve a full study of the whole spectrum of LNG transportation.

- **Relationship with the Hull geometry**

The external surface shape of the hull is a significant parameter for the LNG carrier costs because it directly influences the total added resistance of the hydrodynamic form which leads to the estimated power required to propel the vessel at the required service speed. Since the ship floats on water, this added resistance cannot be avoided and it varies according to the ship’s speed. The relationship between the number of propellers and the ship’s speed is shown in Figure 3-10.

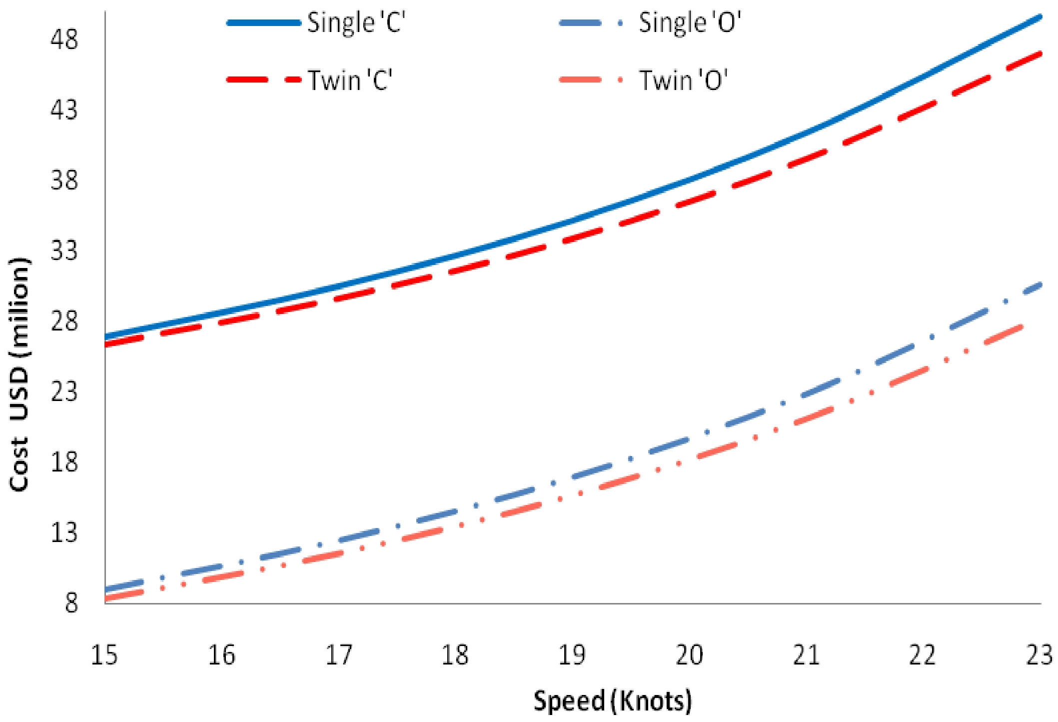


Figure 3-10: The effect of Speed of an LNG carrier, in knots, and the Hull Geometry on Costs

Where:

Single is the single skeg,

Twin is the twin skeg,

'C' is the capital cost, and

'O' is the operational cost.

Figure 3-10 shows the effect of the ship's speed and the type of hull geometry on costs. As the speed increases, both the capital and operational costs per year also increase. Since an increase in the speed requires additional propulsive power, and this power is related to the cost of the engine (Woud and Stapersma, 2002) this will thus increase the capital costs, as illustrated in Figure 3-11. Similarly this additional power requires additional fuel which will also increase the operational costs due to the increase in fuel consumption. These cost increments are similar to those that have been described by Perakis (2002) and IOCS (2005). However, an increase in speed will decrease the journey time and hence the fuel consumption per trip will need to be considered, rather than the daily rate of fuel consumption.

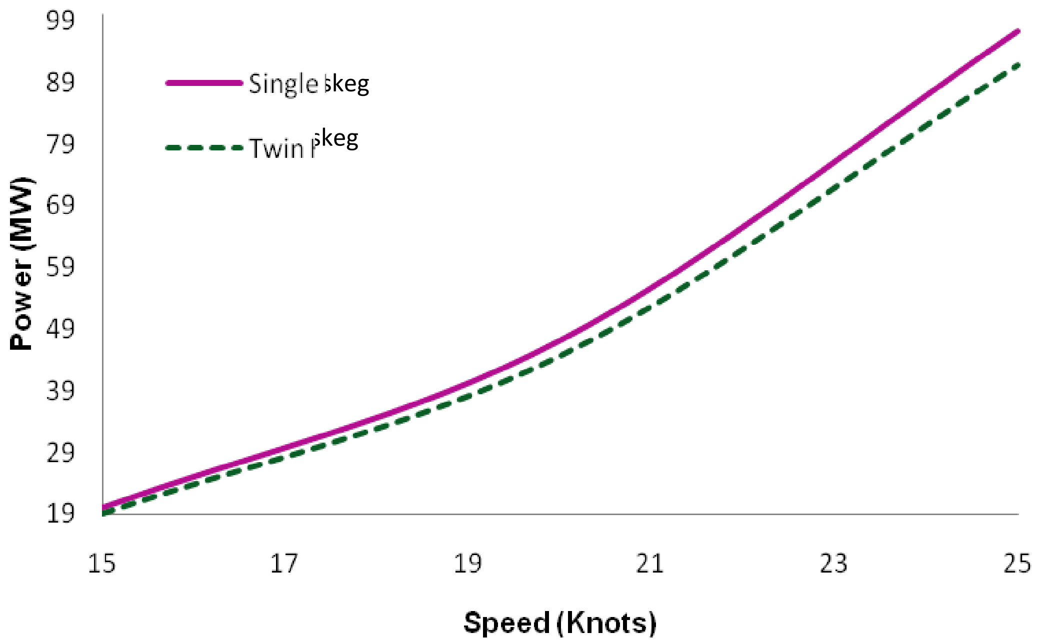


Figure 3-11: The effect of Speed of an LNG carrier in knots and the Hull Geometry on Power in MW

On average the capital costs for the twin skeg is three to five percent lower than that for a single skeg. Similarly, the operational cost for the twin skeg is eight to nine percent lower than that for the single skeg. This reduction agrees with the research carried out by Jin et al. (2006) and Kim and Lee (2005).

Although the twin skeg hull can minimise capital and operational costs, this type of hull form might have conflicts with the size of the ship and other LNG carrier components. Therefore, a holistic approach is required in order to handle this problem.

- **Relationship with the Power prediction**

The two main parameters that are involved directly with the power prediction are (1) required service speed of the ship and (2) total resistance of the ship through a seaway. The total resistance of a ship through a seaway has been discussed previously through the relationship with the effect of ship size (the stern shape will differ between single and twin skeg). For a ship's performance, as the speed is increased, the power required will increase as well as, shown in Figure 3-12.

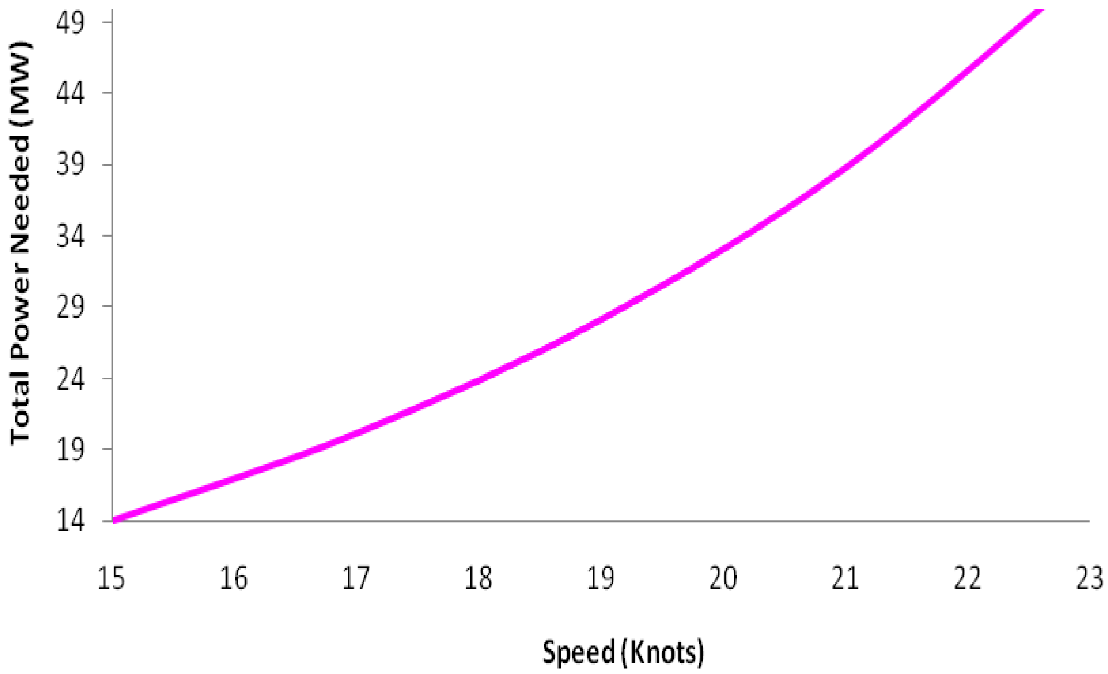


Figure 3-12: The effect of Speed of an LNG carrier in knots on the Total Power Required

Like any type of mechanical transportation system, once the accelerator has been pressed, the speed of the engine will increase. This is due to the increase in fuel in the combustion chamber and more energy being converted and eventually this energy will be transferred to turn the propeller or wheels. As the speed increases, more fuel will be burnt and hence more power will be produced. However, each engine has its own limitations; thus selection of service speed for a vessel must consider not only engine limitations but other factors such as the size of the ship and how this will interact with all the other main components.

In conclusion, based on the effects of the main components and the relationships between them, it is clear that the decision making process will never be straightforward. Moreover, in a real situation, such as for LNG transportation, the ship-owner must have a number of LNG carriers in order to accomplish contract requirements in a given time period. Thus, it creates another challenge to the ship-owner to efficiently manage the fleet. Failing to have the correct size and capacity of fleet will end up failing to maximise the profits of the company. The following subchapter discusses the structure and nature of an LNG carrier fleet.

3.3. LNG carrier Fleet

A fleet consists of a group of, usually similar, carriers that collectively transport a fixed amount of cargo between two ports over a fixed period of time and for a fixed cost (Perakis, 2002). The number of carriers in the fleet and their capacity is heavily dependent on the amount of LNG to be delivered annually, as stated in the contract. The number of carriers can vary according to the capacity and speed of the vessels (Lamb et al., 2004). In addition, fleet operations, scheduling, routing, scheduled maintenance and fleet design can contribute to the development of the overall configuration of a shipping fleet (Perakis, 2002). Specialised long haul carriers with known operating routes, such as LNG transportation, depend on the following factors: the ship's daily running costs, voyage costs, costs at sea, costs in port and daily lay-up costs (Powell and Perakis, 1997), as well as the average number of round trip voyages per year, lay-up costs of the carrier and anticipated number of lay-up days per year (Perakis, 2002).

In terms of a mathematical formula, the number of carriers in a fleet can simply be calculated by dividing the amount of LNG that needs to be delivered in one year by the capacity of a single carrier operating in a single average year. This assumes that all of the vessels have the same capacity, the same speed, and sail the same route, and this is an ideal situation that allows for no down time, either scheduled or unanticipated. The total amount of LNG that needs to be delivered to a specified port in a year can be calculated based on the information stated in the contract between the two parties, i.e. the total amount of LNG over the stated period assuming a uniform delivery per e.g. month. The relationship between the inputs and outputs of a fleet size model is shown in Figure 3-13.

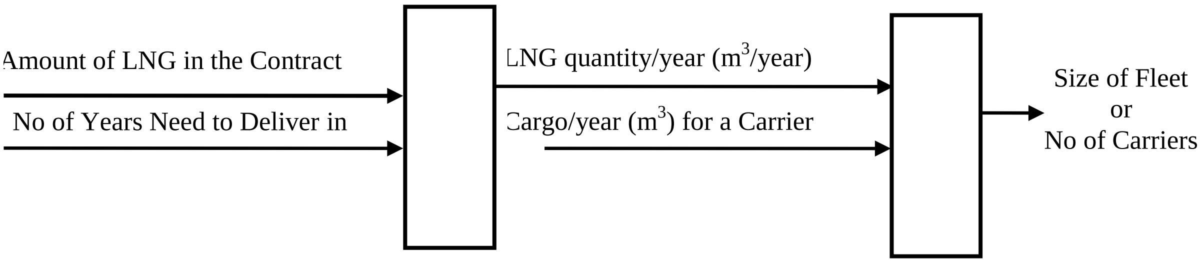


Figure 3-13: The Inputs and Outputs of the Simplified Fleet Size Model

The amount of cargo that can be delivered within a year long period by a single carrier is a function of the number of round trips that are possible per average year by a single carrier and its cargo capacity. Since the capacity of an individual cargo carrier depends on the size of the ship, the number of carriers will also vary accordingly. Meanwhile, the number of trips is a function of the round trip distance, the vessel's service speed, days in both ports per round trip and the days in service per year (Buxton, 1976). Speed is a high impact factor on the size of the fleet. The faster the ship sails, the smaller may be the size of the fleet or the capacity of an individual carrier. However, this will result in an increase in operation costs due to the increase in fuel consumption.

Most of the time, the results produced from this model will not be an integer number but in reality, there can clearly be no 'fractions' of a ship; hence it needs to be rounded up or down and analysed on a multi-year basis. The decision to round up or down is based on the judgement of the ship-owner. In the case of rounding up, the delivery date will be shorter, thus the completion of the total volume of LNG delivered according to the contract will end earlier than the due date. There is generally nothing wrong with delivery of the goods being earlier as long as the customer and its receiving port has no problems or difficulty in handling and processing an increased volume of LNG being delivered in a period of time, in fact it shows that the shipping company has good size fleet and has performed good fleet management. Moreover, they can then charter one or more of the ships to another company for additional income. In another scenario, this spare time can be a money saver, in unanticipated cases. For example, where carriers face problems, e.g. weather and technical, which can result in a delay to the delivery of goods according to the agreed schedule. On the other hand, if the ship-owner wants to round down the number of vessels, the shortfall in capacity can be covered by chartering an additional carrier for a short period of time, or sailing at a higher speed, in order to comply with the contract.

3.3.1. Fleet optimisation

Definitions of fleet size optimisation vary somewhat, however, the objective is generally to find the ideal number of ships to deliver the goods according to the contract and to reduce overall fleet costs. According to Powell and Perakis (1997), optimisation of an entire fleet is normally based on economic criteria such as profitability and income, which is a combination of fleet operations, scheduling, routing and fleet design, etc. Christiansen et al. (2004) explained that port fee payments per ship, port size limitations, and local and international laws that apply to ships' sailing routes are among the factors that determine scheduling and routing decisions which in turn affect a fleet's size. Wu (2009) categorised optimal fleet composition into three groups, namely: labour, fuel and intermediate materials (overall operation costs, minus labour and fuel), while List et al. (2003) suggested that fleet development is a function of demand, operating network and costs. In List's study, costs referred to fleet ownership costs, fleet operating costs and contractual service quality penalties.

However, several studies have been performed using different input variables in examining fleet optimisation, such as those by Wu (2009). He used an economic model to seek a solution regarding optimal fleet capacity in the Taiwan container shipping market. Labour, fuel, capital Investment and a technology index, which included the sailing distance, were taken as input parameters. The method was used to monitor the performance of the fleet development in three major Taiwanese container shipping companies. The results of this study indicated that the development of the Taiwan container fleet has improved significantly during the past decade.

A group study by List et al. (2003) regarding the robust optimisation of fleet planning under conditions of uncertainty, focused on two aspects: (1) future demands and (2) the productivity of individual carriers. They suggested that fleet development is a function of demand, network and costs. This technique was applied to a two-stage stochastic optimisation. Their study developed a solution procedure to assess the impacts of uncertainty on fleet sizing development. A similar study was reported by Ming et al. (2009) in which they used a Grey-Markov chain approach in order to model uncertain conditions.

It is hard to differentiate fleet size optimisation in terms of operation from a purely economic optimisation perspective due to their complex relationships. According to Veenstra and Ludema (2006), there are seven relationships between operational design and the economic performance of ships: (1) mission definition (distance between two geographic points within a given time and price); (2) performance and physical parameters including the amount of cargo to be carried, transit speed, necessary equipment to handle the cargo, and time for loading and unloading; (3) operational deployment (identification of the ship, description of route, travelled distance and bunkering locations); (4) operational life cycle (i.e. the contract length); (5) utilisation requirements (i.e. sustained speed, predicted fuel consumption); (6) effectiveness factors, including berth availability windows for arrival in both loading and unloading ports; and (7) ocean environments including route, no loss of waste or BOG, and summer and winter draught limitations.

A few methods have been used to estimate the operation and capital costs of vessels. These include a study by Lee (1999) that used genetic algorithms and the Hooke and Jeeves method based codes to minimise the building and operation costs. Lee concluded that the operation cost is highly dependent upon the operating speed. Dimopoulos and Frangopoulos (2008) have proposed a combination of simulation methods and particle swarm optimisation techniques in order to solve problems regarding an LNG carrier's energy systems and the associated production of boil-off gas in order to maximise the Net Present Value (NPV) of the investment. Turkmen and Turan (2007) have modified the multi-objective genetic algorithm (MOGA) and weighted evaluation of crowding distances in order to improve a Ro-Ro passenger vessel design from both safety and economic perspectives. Powell and Perakis (1997) have developed an optimisation software package, to minimise the total operating cost and lay-up costs. Galareh and Meng (2010) used mixed integer linear programming in order to find the optimum for fleet size, vessel speed, and route frequency for short term planning requirements, while, Lamp et al. (2004) produced the MSDSS tool for both operating cost and life cycle cost analysis, however, they ignored the initial capital cost.

There are other considerations that need to be taken into account in optimising a fleet size, and one of them is in global financial problems. According to Ming et al. (2009), the current global financial crisis has impacted negatively on some of the shipping fleets. The impacts include a reduction in demand leading to the cancellation of some existing contracts and in additional charges such as an increase of steel price during the building of the ship which generally takes a long period of time. Even though this current crisis has slowed down the shipping market it nevertheless provides the opportunity for companies to optimise and plan the management of their fleet more effectively. In uncertain times, minimising risks and optimising the fleet size can be achieved using two stage-stochastic optimisation programming.

From the review that has been carried out in this study, it suggests that there are many different input parameters that are required for fleet optimisation. Operational cost variables and factors associated with them have been the more common variables used in all fleet optimisation practices. This indicates that the operational cost is clearly one of the predominant factors in determining the number of carriers in a fleet. Although LNG carrier fleet optimisation has not been discussed specifically in any of the reviewed papers, the selected LNG carrier fleet optimisation technique will be similar to those for other types of vessels and will be discussed in detail later in this thesis.

At this stage it is appropriate to discuss the relationships of some of the main independent variables that affect the fleet size.

3.3.2. The Fleet Relationships

The relationships between fleet size, speed and round trip distance, for a given volume of cargo, can be presented graphically as in the example shown in Figure 3-14. The figure, shows that the required number of carriers for given round trip distances of LNG carriers reduces as the ship's speed increases. This is because when ships travel faster, the total time to deliver the same volume of cargo reduces. Since there is a fixed period of time in which to deliver the product, the number of ships can thus be reduced to match this period. On the other hand, the required number of carriers increases by up to 65% as the round trip distance increases from 5000 to 15000 nautical miles. The obvious reason for this is in coping with the demands of the contract.

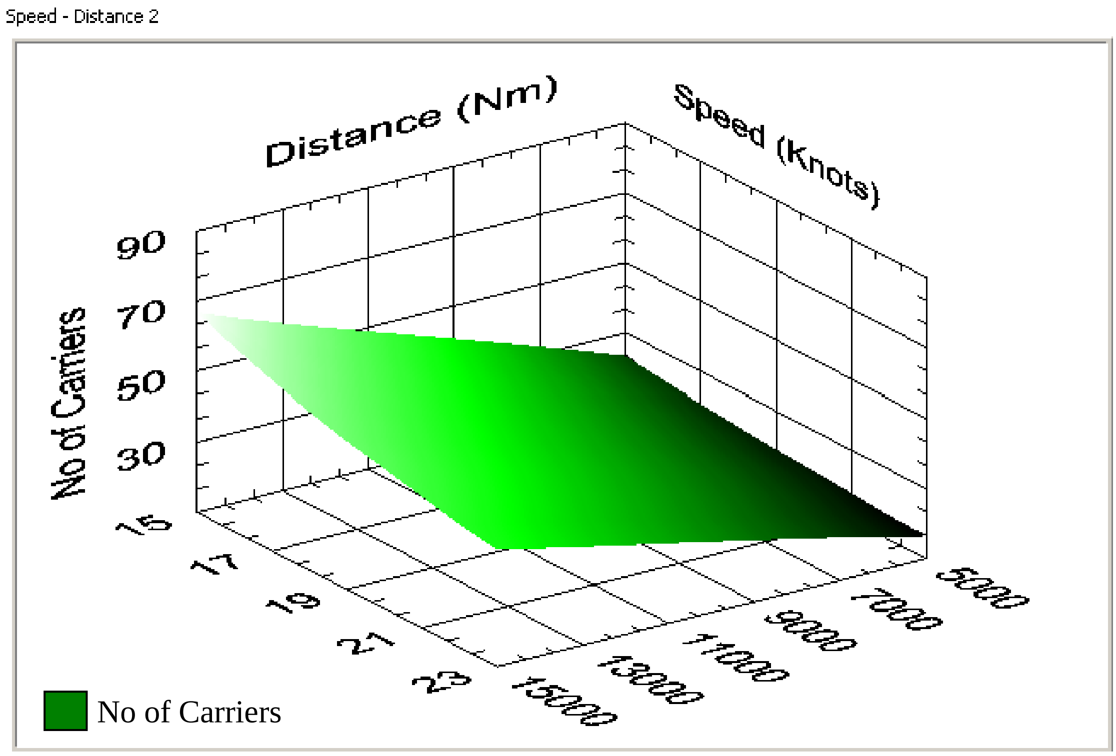


Figure 3-14: The effect of Ship's Speed and Round Trip Distance on the Fleet Size

Another consideration is the relationship between the service speed, the number of contracted years and the size of the fleet, as shown in Figure 3-15.

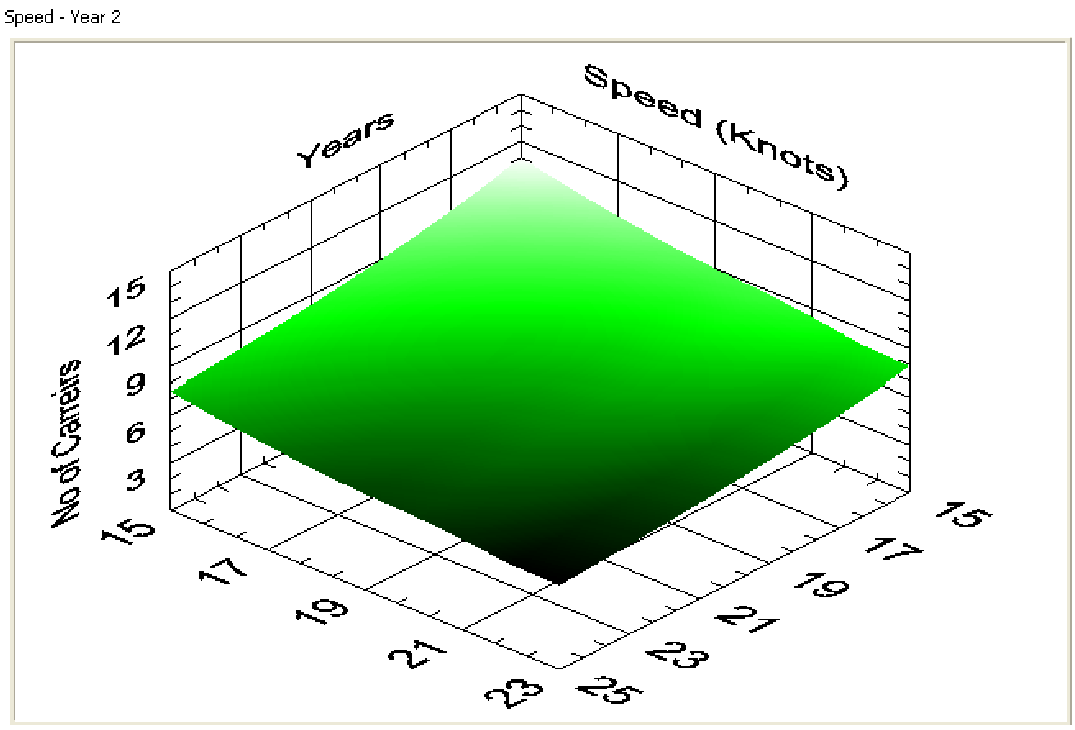


Figure 3-15: The effect of Ship’s Speed and Number of Years on the Fleet Size

Figure 3-15 shows that, as the speed of the ship increases, the number of vessels reduce as would be expected. This reduction is small (approximately between 2 to 4 ships between the extreme range of values considered) compared to the amount of fuel required and its cost as the speed increases. Meanwhile, as the number of years increases from 15 to 25, the required number of carriers reduces by about 30% for the same volume of LNG. This is because as the number of years increases, the amount of LNG to be transported per year will be reduced correspondingly. Thus, the size of fleet that is required is also reduced.

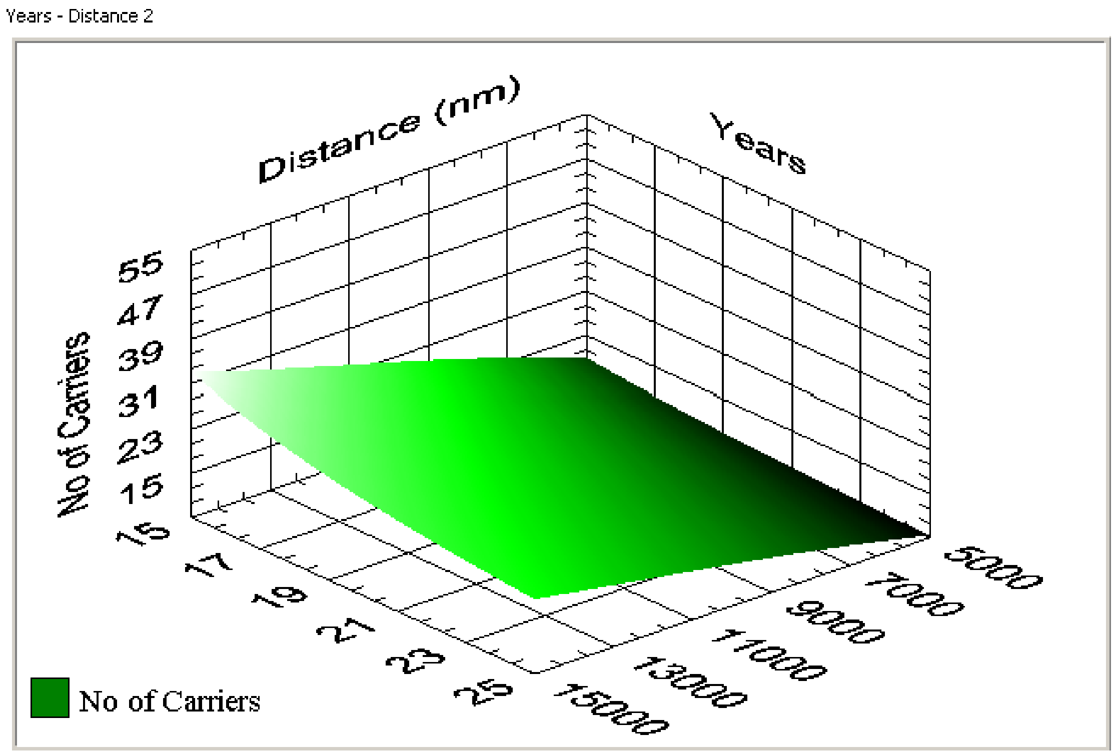


Figure 3-16: The effect of Round Voyage Distance and Contract Durations on the Fleet Size

Figure 3-16 shows the relationship between the trading round trip distances, the number of contract years and the fleet size. As it can be seen, when the number of years increases, the required number of ships is reduced. This assumes a fixed total volume of LNG to be delivered during the period of the contract; hence fewer vessels would clearly be required. Since the fleet size, of identical vessels, can be determined by dividing the total amount of LNG to be delivered in a year by the amount of LNG that can be delivered in a year by a single carrier, an increase in contract period will reduce the amount of LNG per year, which eventually reduces the number of ships in the fleet.

An increase in the round trip distance could lead to an increase in the fleet size. This is because the amount of cargo that needs to be delivered within a year by a single carrier is a function of the maximum number of trips per year with a single carrier cargo capacity. Hence, as the distance of the round trip increases, the number of trips possible per year will be reduced and this will result in an increase in the numbers of carriers.

As the round trip distance between the two ports increases, the number of carriers assuming a constant speed also increases. This increment is due to the number of trips per year reducing as the distance increases. Thus in orders to accomplish the contract's delivery requirement, additional ships are or may be necessary as shown in Figure 3-17.

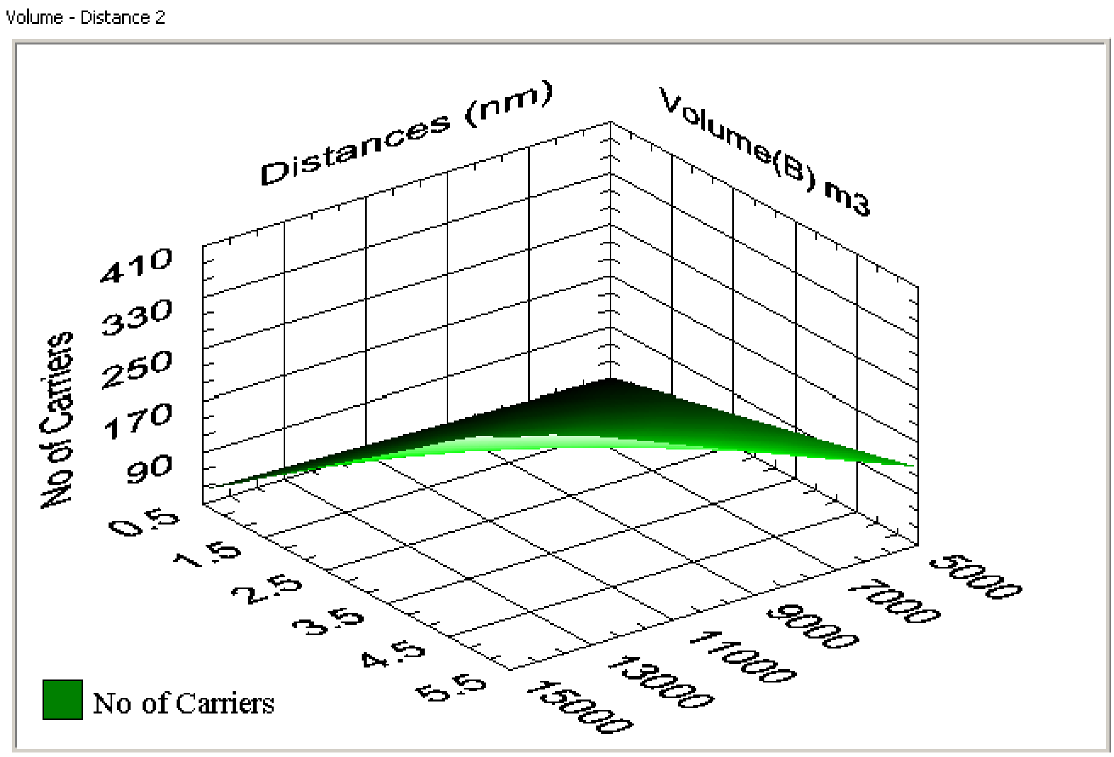


Figure 3-17: The effect of Round Voyage Distance and Cargo Volumes on the Fleet Size

In the case of total contract cargo volume, as discussed before, additional numbers of ships are required in order to cope with an increase in volume demand. As a result, the capital and operational costs, which are based on a single ship, do not change per ship with increases in distances and volumes. The total capital and operational costs can thus be calculated by multiplying these costs by the number of vessels that are needed.

Figure 3-18 explains the relationship between the cargo volume per contract, the contract duration and the number of carriers. As the volume in the contract increases, the volume per year also increases for a given fixed period. Hence when this volume is divided by the amount of LNG that can be delivered by a ship in a single period of one year the numerical results also record an increase in number of vessels required. This number represents the size of the fleet rounded to the nearest integer.

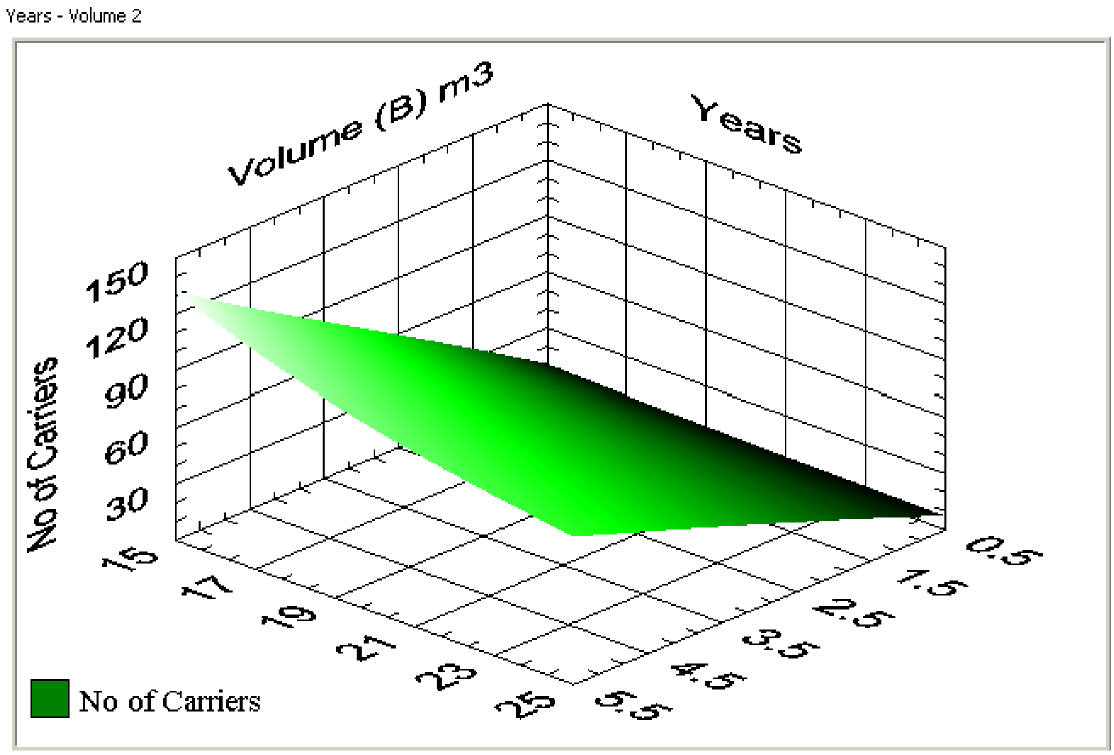


Figure 3-18: The effect of Cargo Volume and Contract Duration on the Fleet Size

As mentioned earlier, an increase in the contract duration for a fixed volume of LNG to be delivered will increase the round trip days which will eventually reduce the number of trips possible in a year. A reduction in trips will allow for a lower number of ships and this explains the reduction in fleet size as the duration increases.

It is clear from the discussions above that the potential interrelationships between the principal systems of an LNG carrier are complicated. Changing any system variables will affect, to some degree, the whole ship system including the overall cost of the LNG carrier as illustrated in figure 2-11. Thus, the results of this study indicate the need for a holistic investigation of the relationships between all the components. This investigation may be performed by creating an LNG carrier simulation based on all of the variables that have been considered. An overview of the inputs and outputs of all variables is illustrated in Figure 3-19.

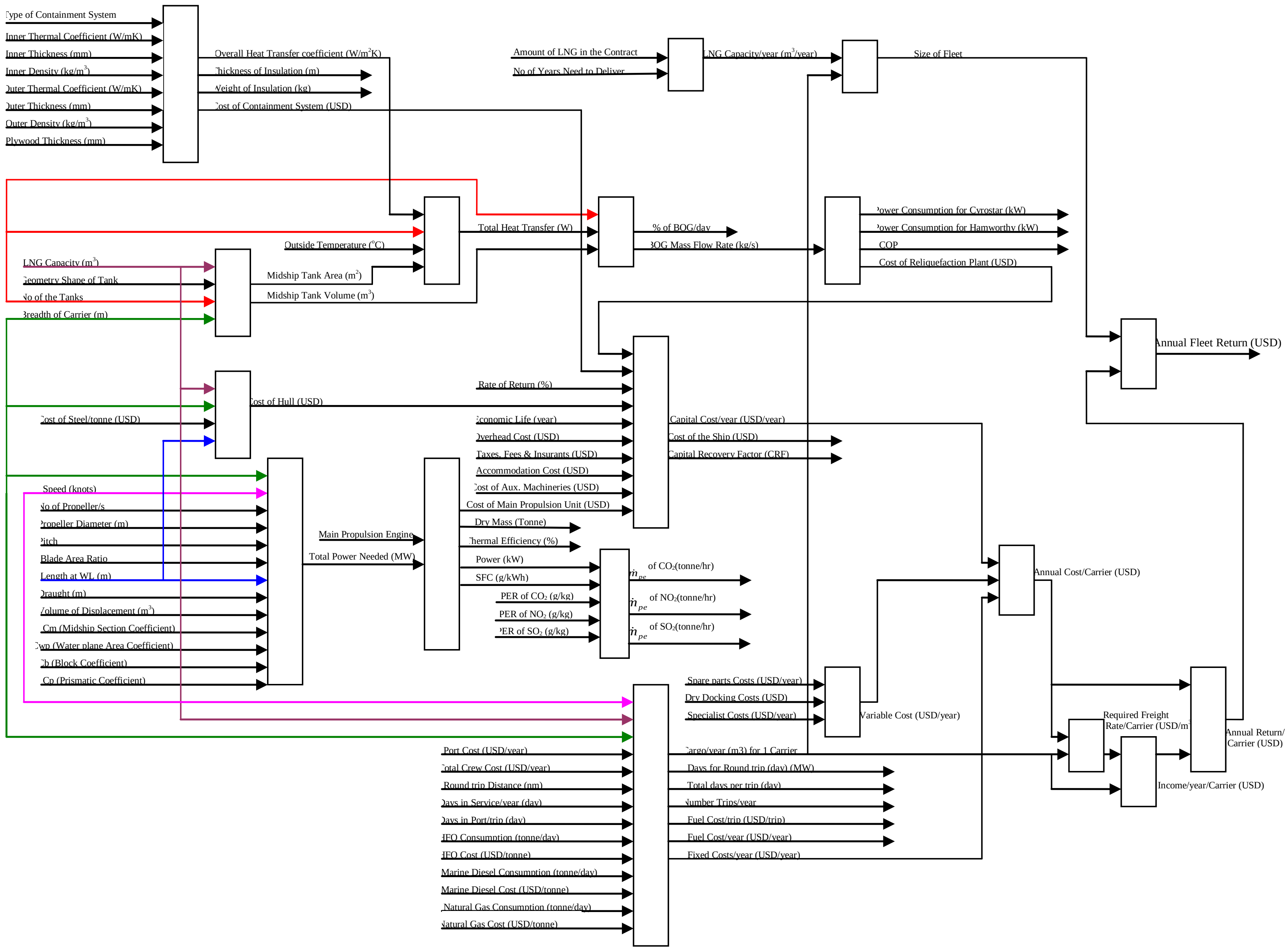


Figure 3-19: The Inputs and Outputs of the LNG carrier Main Components

3.4. Chapter Summary

The purpose of this chapter was to provide an understanding of the principles involved in the LNG carrier design process, for main systems selection. This can be achieved in two steps. Step one defines the relationships between all of the main components of an LNG carrier, while step two extends these relationships into a fleet size.

Understanding each component and the inter-component relationships requires detailed investigation into the behaviour of components relative to any changes in the multitude of variables. The main challenge is to consider and adapt all of the possible constraints within each component. Two variables that affect the main components of an LNG carrier have been studied carefully; the size of the carrier which represents the cargo capacity, and service speed of the carrier. Since all the main components of an LNG carrier are inter-related, changing these two main variables, will impact on all the main components. Graphical presentations have been provided for better illustration of each relationship interaction.

Furthermore, if there are a number of identical carriers in the fleet, as is normal for a company, the interrelationships becomes more complicated and create a challenging situation for the engineers to deal with. One of the ways to accommodate this kind of problem is by creating a view of the whole LNG carrier which consists of a ‘system of the systems’ simulation model. Three dimensional graphs have been presented for the purpose of clarifying the investigated relationships. Speed, round trip distance, volume of cargo and the number of contract years have been identified as the main variables that affect the size of the fleet.

Since the LNG carrier simulation model links all of the main components, any changes in an input parameter will produce different sets of results according to their theoretical formulation. This capability is essential to the aim of this study which is to select the best combination of components for certain tasks. Before the selection of an optimal combination of components can be established however, comprehensive systematic simulation data, which considers all possible combinations, must be collected. This can be done by systematically varying the selected variables in a simulation model. The details of this process are discussed in the next chapter.

4. Model Development for the LNG carrier Simulation

Summary

The overall aim of the work presented in this chapter was to generate simulation data for the LNG 'system of systems' and to use this to train an ANN model from which results were then generated and analysed

The objectives of this chapter are thus summarised as follows:

- To describe the process of building the simulation model
- To describe the data generation process from the simulation model.
- To develop an equivalent Artificial Neural Network model.

4.1. Introduction

Simulation can be described as the process of using a computer program to duplicate the behaviour of complex components in order to determine the corresponding responses, under various investigated scenarios where the inputs change. According to Chung (2004), simulation has four main advantages: (1) the ability to understand the operation of a complex system without the need to stop and shut down the system; (2) to be able to improve the existing system performance once its behaviour has been understood; (3) to be able to predict the performance of a new system; and (4) the ability to gain information without disturbing a sensitive actual system, such as a security system at an airport. However, similar to many other methods, simulation is not free from limitations. These limitations include an inability to solve problems by itself, it's expense in terms of manpower and computer time, failure to give accurate results if the input data are inaccurate, and results that may be easily misinterpreted with errors that may be difficult to trace (Neelamkavil, 1987).

A 'model' can be defined as an idealised representation of a real physical entity. It is a simplified version of more complex forms, processes, and ideas which may enhance the understanding of behaviour and facilitate prediction of a system through being amenable to mathematical analysis (Bekey, 2003; Neelamkavil, 1987). The model can provide a quick, cheap and unobtrusive alternative aid to learning, design, prediction and evaluation. Models can be divided into three groups (Hoover and Perry, 1989): (1) iconic, as they attempt to resemble the real physical system e.g. an LNG carrier model; (2) analogue, as they represent or emulate system behaviour, such as for the flow of LNG through pipes; and (3) symbolic, which is neither iconic nor analogue, but is based on logic flow: such as a functional relationship between two spaces in time e.g. a mathematical model.

Models can be further classified into two other groups which are descriptive and prescriptive. Descriptive models will produce results when there is change in the input parameters, but the results that they produce may not necessarily be the best solution to the given problem (Law and Kelton, 2000). The process of finding the best solution is totally in the analyst's judgement, simulation modelling being a good example of this type of model. Meanwhile, prescriptive models are an advanced group. The results may be analysed using optimisation tools in order to formulate and find the best solution to a given problem (Hoover and Perry, 1989). An example of this type of model is multiple criteria optimisation which will be discussed later in this thesis.

A mathematical model, on the other hand, is a representation, in a form that is amenable to mathematical analysis, of a process, device, or concept using a number of variables defined to represent the inputs, outputs, and internal states of the device or process. According to Karplus (2003), a mathematical model can produce two types of information: (1) knowledge of the system being modelled; and (2) data observations from a system's inputs and outputs.

In principle, the procedure for the specific component modelling adopted in this thesis was to create a computer programme based on mathematical models of the whole set of possible components of an LNG carrier. The simulation investigation then changed the input variables systematically, enabling one to sense the complexity and interaction of the various problems. The appropriate combination and characteristics of the individual components were then identified in order to reduce the capital and operational costs of the LNG carrier. Prior to carrying out any simulations for this study, all related components of the LNG carrier needed to be defined in terms of mathematical models. The process of transforming each component is explained in the following appendices: the containment system (appendix 1), the reliquefaction plant (appendix 2), the power prediction (appendix 3), the fleet size, and the life cycle cost analysis (appendix 4). Three of the components that have been explained in Chapter Two (propulsion unit, mission profile and hull geometry) were not defined in terms of mathematical models for the following reasons:

(1) Propulsion unit: because part of the purpose of this is study was to select the main engine from the market, based on the power requirement predictions, the calculation of emissions has been introduced in order to measure the amount of pollutants that will be released into the atmosphere due to combustion from the selected engine (appendix 5).
(2) Mission profile: this involves definition of the input variables to the LCCA.
(3) Hull geometry: the selection between single or twin skeg is included in the power prediction mathematical models; however, the calculation of ship steel weight is introduced for the purpose of finding the build cost of the ship (appendix 6).

A simplified diagram to show all of the LNG components involved in the overall simulation model is illustrated in Figure 4-1.

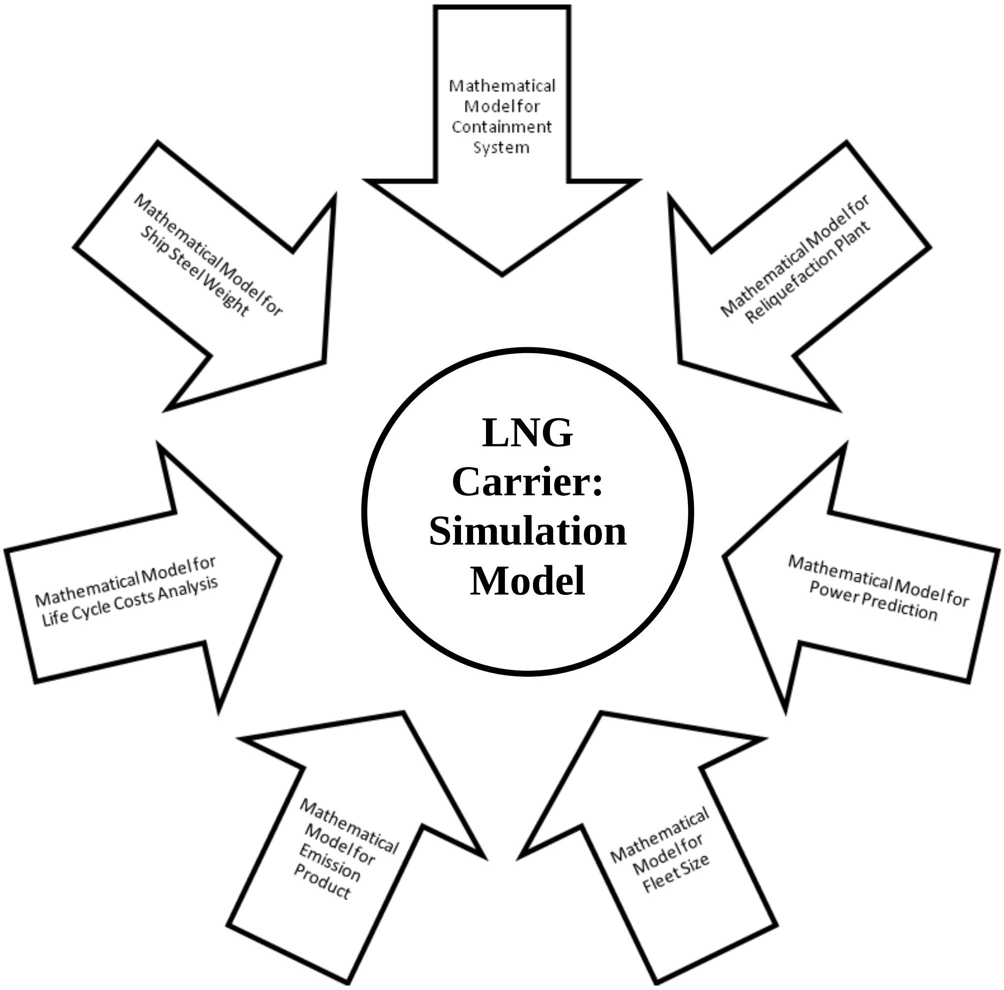


Figure 4-1: LNG Carrier Components Simulation Models

4.2. Development of an Holistic Simulation Model for the LNG Carrier

A simulation software package named LabVIEW 8.2 was used to create a simulation model for the LNG carrier components. LabVIEW is an acronym for **Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench and is a platform and development environment for a visual programming language. This LabVIEW package ties the creation of user interfaces known as ‘front panels’ into the development cycle. The LabVIEW programs and its subroutines are called virtual instruments (VIs) or sub-virtual instruments (SubVIs). Each of the VIs has three main components, a block diagram, a front panel, and a connector panel.

The mathematical models of the LNG carrier components were transformed into the input form required for the LabVIEW programme. Each of the components was then linked with the others that have the same input or output variables. Some additional information generated as output parameters was not linked to other components such as thickness of insulation and weight of insulation. Since the focus of this thesis is on reducing the fleet size, total costs and pollutant emission products, only the outputs related to the given criteria were linked together. Additional information was retained as it may be useful to other applications or provide justification for certain facts, such as the thickness and weight of the containment system. The LabVIEW block diagram for the LNG carrier simulation model is illustrated in Figure 4-2.

Once the LNG carrier simulation had been developed, the user was able to select any combination of components to study. These selections were not limited to any particular types or forms, the user may insert or change the values in the inputs variables e.g. insulation thickness and materials, or the pressure and the temperatures of the cycles in the reliquefaction plant. The capability of inserting any value shows the flexibility of this simulation which gave advantages in terms of carrying out further investigations on this system. However, before any further investigations could be performed, a set of data needed to be generated from this simulation.

The components illustrated in Figure 4-1 were translated into a LabVIEW programme, as shown in Figure 4-2. This provides a holistic simulation model for the LNG carrier which allows the researcher to investigate the interrelationships between the parameters. The model was used to generate a data set to investigate all possible combinations of inputs.

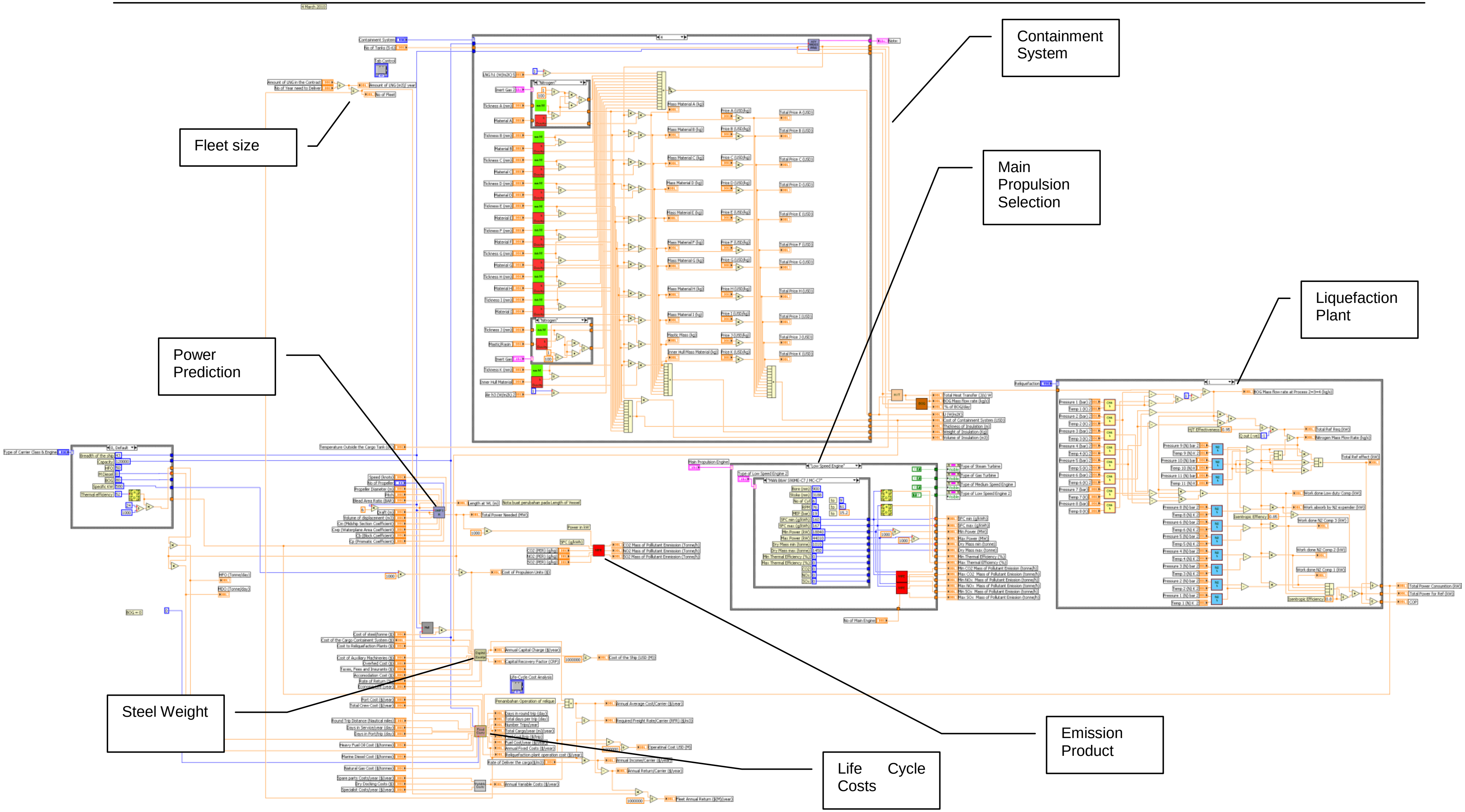


Figure 4-2: LabVIEW's Block Diagram for the LNG carrier Simulation Model

4.3. The Generation of Data from Simulation

There were a few steps that needed to be taken in generating the data for an LNG carrier, starting with selecting the most important independent variables of each component in the overall ship components, and in operating parameters. This was an important step because there were more than 50 independent variables in the full range of LNG carrier components, and selecting those variables likely to be of most significant impact on each component not only reduced the number of parameters but also reduce the amount of computing time and user input effort (Rao, 1996). Later, a practical range for each of the selected variables was set according to restrictions or limitations in order to ensure that any solutions that were obtained were technically sound and economically feasible (Deb, 2005). The next step was to start feeding the simulation model with systematic changes in the variables. Changing each variable systematically while keeping the others constant will give all possible solutions for a particular problem. A simple flow chart of the data collecting process is illustrated in Figure 4-3.

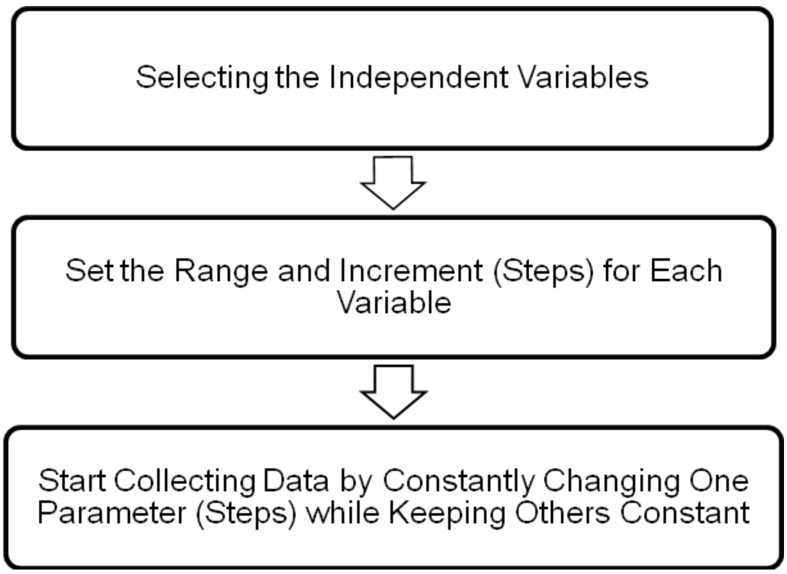


Figure 4-3: Flow Chart for the Data Collection Process

4.3.1. Selecting the Variables

The selection of the most high impact variables was a crucial step especially when dealing with a large number of variables. As has been previously mentioned, the whole range of components of an LNG carrier is linked together due to their interdependency; hence, any changes in one or more variables will affect one or more others. Depending on the objective function of the problem, a variable can be a component by itself, which has a high influence on the overall results that are generated. Therefore, a complete understanding of each of the components is necessary in order to select the right variables to represent the whole picture of the given problem.

In this study, eight independent variables were identified as being the ones that would have a high impact on the total cost of an LNG carrier. They are: (1) the type of carrier class and propulsive engines; (2) the amount of LNG to be transported stated in the contract; (3) the number of years set in the contract; (4) the round distance between the export and import ports; (5) the carrier's required speed; (6) the type of containment system to be selected; (7) the type of reliquefaction plant chosen; and (8) the number of propellers, which indicates the shape of the hull form to be constructed. The results from the simulation models give the two cost classifications: namely, the capital costs and the operational costs. However, additional results have been produced alongside the costs such as fleet size and the emission levels.

Four selected variables are components by themselves: the containment system, the reliquefaction plant, the propellers and the LNG carrier class and engines. The values of each of these elements were fixed to ensure consistency in the results throughout the process. These values are illustrated in Table 4-1, Table 4-2, Table 4-3, and Table 4-4 respectively.

Table 4-1: The Fixed Parameters for the Cargo Containment Systems

Type of Containment System		**No96**	**MARK III**	**CS1**	**MOSS**
Inner Barrier	Material	INVAR	Stainless Steel	INVAR	Aluminium
	Thickness (mm)	0.7	1.2	0.7	30
	Price (USD/m^2)	268.25	3.156 (USD/kg)	268.25	1323.78
Inner Insulation	Material	Perlite	Polyurethane	Polyurethane	Phenolic
	Thickness (mm)	210	80	80	180
	Price (USD/m^2)	0.0518	9.39	9.39	4.41
	Density (kg/m^3)	50	11	11	80
Outer Barrier	Material	INVAR	Triplex	Triplex	-
	Thickness (mm)	0.7	1	1	-
	Price (USD/m^2)	268.25	7.83	7.83	-
Outer Insulation	Material	Perlite	Polyurethane	Polyurethane	Polyurethane
	Thickness (mm)	280	160	160	180
	Price (USD/m^2)	0.0518	9.39	9.39	9.39
	Density (kg/m^3)	50	11	11	11

Table 4-2: The Fixed Values for the BOG Reliquefaction Plants

Items	**Percentage**
Heat Transfer Effectiveness	95
Isentropic efficiency For Nitrogen Expender	85
Isentropic efficiency for High and Low Compressors	80

Table 4-3: The Fixed Values for the Propeller

Items	**Values**
Propeller Diameter (m)	8
Blade Area Ratio	0.7
Pitch (m)	6.87
Shaft Efficiency	0.98
Power Margin (1 + x)	1.2
Propeller Efficiency	0.65

Table 4-4: The Fixed Values for the Carrier Classes and Engines

LNG Carrier Classes & Engine	Dimensions	
Small Conventional & Slow Speed Engine	Breadth (m)	43
	Capacity (m^3)	120,000
	Specific Cost (USD/kW)	580
	Thermal Efficiency (%)	52
Small Conventional & Medium Speed Engine	Breadth (m)	43
	Capacity (m^3)	120,000
	Specific Cost (USD/kW)	319
	Thermal Efficiency (%)	46
Small Conventional & Gas Turbine	Breadth (m)	43
	Capacity (m^3)	120,000
	Specific Cost (USD/kW)	261
	Thermal Efficiency (%)	40
Large Conventional & Slow Speed Engine	Breadth (m)	46
	Capacity (m^3)	150,000
	Specific Cost (USD/kW)	580
	Thermal Efficiency (%)	52
Large Conventional & Medium Speed Engine	Breadth (m)	46
	Capacity (m^3)	150,000
	Specific Cost (USD/kW)	319
	Thermal Efficiency (%)	46
Large Conventional & Gas Turbine	Breadth (m)	46
	Capacity (m^3)	150,000
	Specific Cost (USD/kW)	261
	Thermal Efficiency (%)	40
Q-flex & Slow Speed Engine	Breadth (m)	51
	Capacity (m^3)	210,000
	Specific Cost (USD/kW)	580
	Thermal Efficiency (%)	52
Q-flex & Medium Speed Engine	Breadth (m)	51
	Capacity (m^3)	210,000
	Specific Cost (USD/kW)	319
	Thermal Efficiency (%)	46
Q-flex & Gas Turbine	Breadth (m)	51
	Capacity (m^3)	210,000
	Specific Cost (USD/kW)	261
	Thermal Efficiency (%)	40
Q-Max & Slow Speed Engine	Breadth (m)	56
	Capacity (m^3)	250,000
	Specific Cost (USD/kW)	580
	Thermal Efficiency (%)	52
Q-Max & Medium Speed Engine	Breadth (m)	55
	Capacity (m^3)	250,000
	Specific Cost (USD/kW)	319
	Thermal Efficiency (%)	46
Q-Max & Gas Turbine	Breadth (m)	56
	Capacity (m^3)	250,000
	Specific Cost (USD/kW)	261
	Thermal Efficiency (%)	40

4.3.2. Setting the Allowable Ranges of each of the Variables

The range was set due to limitations of the behaviour or the physical constraints of the equipment, current practice, the rules and regulations imposed on the components or the various and many combinations of them. Varying the parameters systematically produced a set of results that showed the effects of each change. It was done by dividing the whole range of sets into equal increments. The selected range set and step increments for the LNG carrier components chosen for this study are shown in Table 4-5.

Table 4-5: The Range and Increments for Independent Variables

Independent Variables	Minimum	Increment	Maximum
LNG Amount in the Contract (B) m^3	0.5	1	5.5
Number of Years to Deliver (Years)	15	5	25
Round Trip Distance (Nm)	5000	5000	15000
Carrier Speed (Knots)	15	2	23

4.3.3. Collecting Results Data from the LabVIEW Simulation Model

The last step of collecting data was to run the simulation program through iterations, systematically changing the variables over their allowed ranges. The numbers of iterations was dependent on the increment values selected. The accuracy of the simulation results depended on the amount of data collected and the incremental values needed to be small to increase the sensitivity. The output data collection was generated automatically by creating multiple loops in the LabVIEW software, as illustrated in Figure 4-4. The SubVI labelled Optima is the LNG carrier simulation model that was explained previously. The inputs and system level outputs of this SubVI are shown in Figure 4-5.

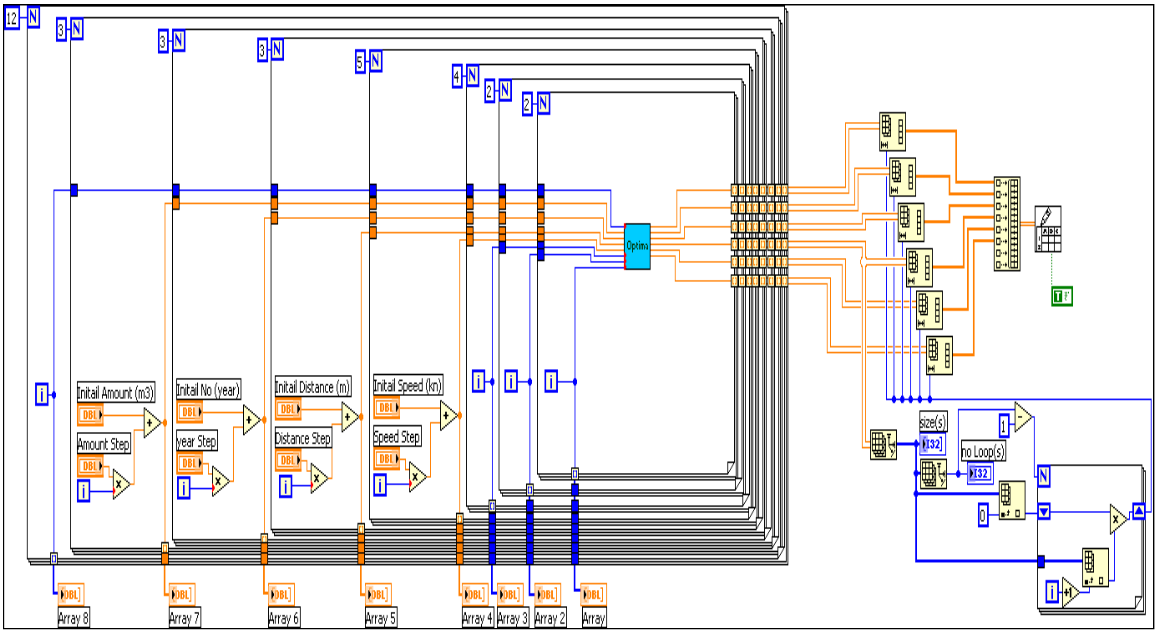


Figure 4-4: Simulation Programme for Output Data Collection

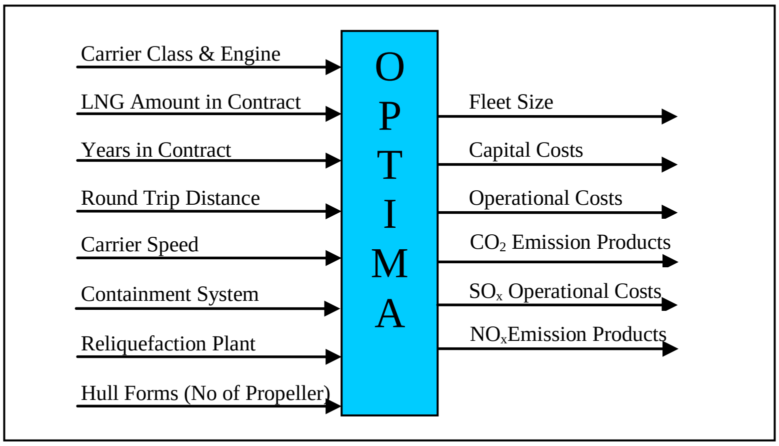


Figure 4-5: Inputs and Outputs of the Simulation Model for LNG Carrier

An example of the results of this overall system data collection process can be seen in Table 4-6. For simplicity of tabulation, some of the terms in the columns such as type of carrier class and engines, containment systems, type of reliquefaction plant, and number of propellers have been replaced with reference numbers. Table 4-7 provides the meaning of the assigned reference numbers.

Table 4-6: Sample of the Simulation Data Table

Type of Carrier Class & Engine	Amount of LNG in the Contract (m) m3	No of Years need to Deliver (year)	Round trip Distance (Nm)	Carrier Speed (knots)	Containment Systems	Type of Reliquefaction Plant	No of Propeller	Fleet size	Capital Cost/ Carrier USD (m)	Operation Cost/ Carrier USD (m)	CO2 mass of Pollutant Emission (tonne/hr)	SO_x mass of Pollutant Emission (tonne/hr)	NO_x mass of Pollutant Emission (tonne/hr)
9	0.5	15	5000	15	5	3	1	11.82	26.97	9.02	7.57	0.05	0.10
9	0.5	15	5000	15	5	3	2	11.82	26.33	8.38	6.98	0.04	0.09
9	0.5	15	5000	15	5	4	1	11.82	26.97	9.00	7.57	0.05	0.10
9	0.5	15	5000	15	5	4	2	11.82	26.33	8.36	6.98	0.04	0.09
9	0.5	15	5000	15	6	3	1	11.82	20.07	8.97	7.57	0.05	0.10
9	0.5	15	5000	15	6	3	2	11.82	19.43	8.33	6.98	0.04	0.09
9	0.5	15	5000	15	6	4	1	11.82	20.07	8.95	7.57	0.05	0.10
9	0.5	15	5000	15	6	4	2	11.82	19.43	8.31	6.98	0.04	0.09
9	0.5	15	5000	15	7	3	1	11.82	21.34	8.97	7.57	0.05	0.10
9	0.5	15	5000	15	7	3	2	11.82	20.70	8.33	6.98	0.04	0.09
9	0.5	15	5000	15	7	4	1	11.82	21.34	8.95	7.57	0.05	0.10
9	0.5	15	5000	15	7	4	2	11.82	20.70	8.31	6.98	0.04	0.09
9	0.5	15	5000	15	8	3	1	11.82	27.71	8.86	7.57	0.05	0.10
9	0.5	15	5000	15	8	3	2	11.82	27.07	8.22	6.98	0.04	0.09
9	0.5	15	5000	15	8	4	1	11.82	27.71	8.84	7.57	0.05	0.10
9	0.5	15	5000	15	8	4	2	11.82	27.07	8.20	6.98	0.04	0.09
9	0.5	15	5000	17	5	3	1	10.52	30.54	12.51	10.90	0.07	0.14
9	0.5	15	5000	17	5	3	2	10.52	29.61	11.58	10.03	0.06	0.13
9	0.5	15	5000	17	5	4	1	10.52	30.54	12.48	10.90	0.07	0.14
9	0.5	15	5000	17	5	4	2	10.52	29.61	11.56	10.03	0.06	0.13
9	0.5	15	5000	17	6	3	1	10.52	23.64	12.45	10.90	0.07	0.14
9	0.5	15	5000	17	6	3	2	10.52	22.71	11.53	10.03	0.06	0.13
9	0.5	15	5000	17	6	4	1	10.52	23.64	12.43	10.90	0.07	0.14
9	0.5	15	5000	17	6	4	2	10.52	22.71	11.50	10.03	0.06	0.13
9	0.5	15	5000	17	7	3	1	10.52	24.92	12.45	10.90	0.07	0.14
9	0.5	15	5000	17	7	3	2	10.52	23.99	11.53	10.03	0.06	0.13
9	0.5	15	5000	17	7	4	1	10.52	24.92	12.43	10.90	0.07	0.14
9	0.5	15	5000	17	7	4	2	10.52	23.99	11.50	10.03	0.06	0.13
9	0.5	15	5000	17	8	3	1	10.52	31.28	12.34	10.90	0.07	0.14
9	0.5	15	5000	17	8	3	2	10.52	30.35	11.41	10.03	0.06	0.13
9	0.5	15	5000	17	8	4	1	10.52	31.28	12.32	10.90	0.07	0.14
9	0.5	15	5000	17	8	4	2	10.52	30.35	11.40	10.03	0.06	0.13
9	0.5	15	5000	19	5	3	1	9.50	35.18	16.98	15.22	0.10	0.19
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
20	5.5	25	15000	23	8	4	2	70.84	43.88	70.93	47.53	0.30	0.59

Table 4-7: Meaning of Assigned Reference Numbers

Column	No	Items
No. of Propellers	1	One
	2	Two
Type of Reliquefaction Plants	3	Hamworthy Reliquefaction Plant
	4	Cryostar Reliquefaction Plant
Type of Containment Systems	5	No96 Containment System
	6	MARK III Containment System
	7	CS1 Containment System
	8	MOSS Containment System
LNG Carrier Classes & Engines	9	Small Conventional & Slow Speed Engine
	10	Small Conventional & Medium Speed Engine
	11	Small Conventional & Gas Turbine
	12	Large Conventional & Slow Speed Engine
	13	Large Conventional & Medium Speed Engine
	14	Large Conventional & Gas Turbine
	15	Q-flex & Slow Speed Engine
	16	Q-flex & Medium Speed Engine
	17	Q-flex & Gas Turbine
	18	Q-Max & Slow Speed Engine
	19	Q-Max & Medium Speed Engine
	20	Q-Max & Gas Turbine

The total number of rows of data generated was 51,840. This was based on 12 types of LNG carrier class and engines, 6 increments of LNG transportation cargo in the contract, 3 steps of years to deliver the LNG in the contract, and the round trip distances, 5 increments of carrier speeds, 4 types of containment systems, and 2 types of reliquefaction plant and hull geometry. The 51,840 rows of data are clearly too many to analyse and evaluate manually.

Moreover, each row provided six different sets of outputs (corresponding to the outputs as shown in Figure 4-5). In total, there are therefore 311,040 cells that each represents different scenario values. The preliminary results from this data were used to investigate the relationships between variables, as explained and illustrated in chapter 3.

The best way to deal with this data is by developing a simplified equivalence for the LNG carrier systems design simulation ‘OPTIMA’ process. This was achieved with the aid of Artificial Neural Networks (ANN). Moreover, this large volume of data, which consists of only numbers, can easily be overlooked, misinterpreted and mistakes, if any, are very difficult to find.

In addition, further computation time would be required in order to generate additional new data for changes to the original input. This raises the idea of a program or a model that could simplify and facilitate selection from the large amount of generated data. Since the ANN was used in this thesis for reducing the decision area and minimising computation time, it is appropriate to understand its background.

4.4. Artificial Neural Networks Model

The Artificial Neural Network (ANN) is a comprehensive data process modelling tool which duplicates the brain's intelligence by using experience to capture and represent complex input and output relationships (NeuroSolutions, 2010). The ANN is similar to the processing function of the human brain in two ways: (1) neural networks acquire knowledge through repetitive learning activities; and (2) the neural network's knowledge is then stored within inter-neuron connections known as synaptic weights (Ok, 2006). The real advantage of ANNs is in their ability to learn the relationships directly from the input and output data given regardless of whether it is a linear or a non-linear relationship.

The ANN method was introduced by McCulloch and Pitts (McCulloch and Pitts, 1943) when they modelled a simple neural network with an electric circuit in order to perform a simple logical function. From that period until 1990, the further studies were focused on the development of the ANN theory itself (Mesbahi, 2007a; Zhang, 1997). From the 1990s onward the focus on theory development was reduced with more concentration on the application of ANNs. This however, does not mean that the ANNs are perfect and do not need further modifications or improvements. In fact the improvement of ANNs has been continuous alongside their applications, and ANNs now are widely applied in solving engineering problems (Ok, 2006; Rao, 1996).

ANN methods have been used to solve problems in many aspects of marine engineering, such as work carried out by Dansman et al. (2002) for reducing the wave resistance of the aft of the hull of a ship, and Lightfoot et al. (2006) studied the impact of welding distortion of steel plate. Predicting the strength of plates with pitting corrosion was a studied by Duo et al (2007), whilst Grimmelius et al. (2007) used ANNs to predict the speed of a diesel engine from the engine load and fuel rack displacement. Other areas in the marine field include the ship design process, ship resistance and power, ship motion, ship production, manoeuvring and ship design optimisation (Mesbahi, 2007a).

Artificial neural networks have many advantages and according to Ok (2006) these advantages can be classified into four main groups:

1. Learning: They have the ability to learn linear and non-linear sets of patterns, and to interpolate data within the trained range accurately.
2. Time: The ANN has a parallel structure which can reduce the computing time and they can provide a response in almost real time.
3. Flexibility: The ANN can accommodate a certain level of interference such as noise signals in the input data without producing significant changes in the results.
4. Tolerance to internal faults: Since the ANN stores redundant information, partial destruction does not completely destroy the network's response capability.

One of the features that make an ANN so unique is the ability to capture the relationships of multiple variables either in input or output data. This unique feature is very useful in a study such as this thesis, especially when dealing with multi-variable optimisation. However, ANNs have drawbacks. Among the disadvantages are the need for a long training time, internal network selection that is based on trial and error, especially for a new problem without prior knowledge, and 'network paralysis', which can happen when the network fails to respond due to very large values given to the internal mathematical 'weights' (Mesbahi, 2003; Roskilly and Mesbahi, 1996).

4.4.1. Fundamentals of Artificial Neural Networks

In order to initialise a typical ANN, it must have the following elements: the most important element is data which consists of input variables (x_1 to x_n) and the required associated output results (Y). These inputs are summed together after being multiplied by individual weight factors (W_1 to W_n). The summation results are fed into an activation function to generate the results which ideally are similar to the required output. The simplified basic model of an artificial neural network is illustrated in Figure 4-6.

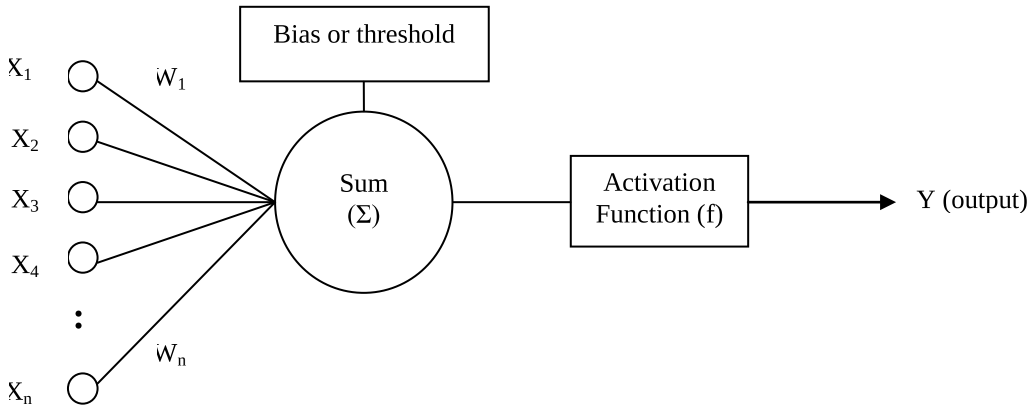


Figure 4-6: Basic Model of Artificial Neural Network

The process of an artificial neural network can be formulated mathematically as (Ok, 2006):

$$Y = f\left[\sum_{k=1}^{n} x_k W_k + b_k\right]$$

Equation 4-1: Artificial Neuron Formula

Where ‘b’ is a scalar bias which acts in a similar manner to the weight ‘W’ and is sometimes known as the threshold.

The activation function f(x), which has been described as the summation of the inputs and weights in the above equation, can be categorised into one of two groups: namely, linear and non-linear functions.

- A linear activation function might simply be: $f(x) = x$
- Examples of non-linear activation functions include:
  - Sigmoid function: $f(x) = \frac{1}{1+\exp^{x}}$
  - Tan-hyperbolic (Tanh) function: $f(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}}$

Where:

x is the input.

The sigmoid and the Tanh functions are the more common activation functions that are used because they introduce non-linearity into the networks which is a common feature of most problems that are encountered in engineering systems (Mesbahi, 2006).

In order to train the software, the initial weights, W, of the ANNs are set as small random values since the network does not know the relationship between the input data and the required output data. As the training develops these weights eventually converge according to computational rules, where the overall final output results meet the required values. The whole purpose of the training process is to teach the ANN to determine the required output value(s) from a given set of input data. Thus the ANN is being taught to emulate the performance of the more complex system that is associated with the data, both input and output.

4.4.2. Types of Artificial Neural Networks

There are many types of network architecture, the most common and popular being single and multilayer feed-forward networks (Zhang, 1997). Single layer feed-forward was the earliest type of network and consists of a single layer of output nodes. If the summation products of the input and corresponding weights are above the threshold (which is normally zero), then the typical activated value is taken as one; otherwise it is minus one (Ok, 2006). On the other hand, multilayer feed-forward networks, also known as multilayer perceptions, has one or more so-called hidden layers.

There are two types of learning algorithms used in ANNs, the 'feed-forward' and the 'recurrent' forms. In a feed-forward network, data only flows in one direction from the input layer to the output layer. Once the data passes through to the next layer, the previous layer will not know the results that were obtained. Conversely with a recurrent or feed-back network, the input layer will receive back the result and use it in its re-evaluation process. These configurations are illustrated in Figure 4-7. There is no rule to select the most appropriate of these learning algorithms and most often it is based on the user's experience and/or the trial and error method.

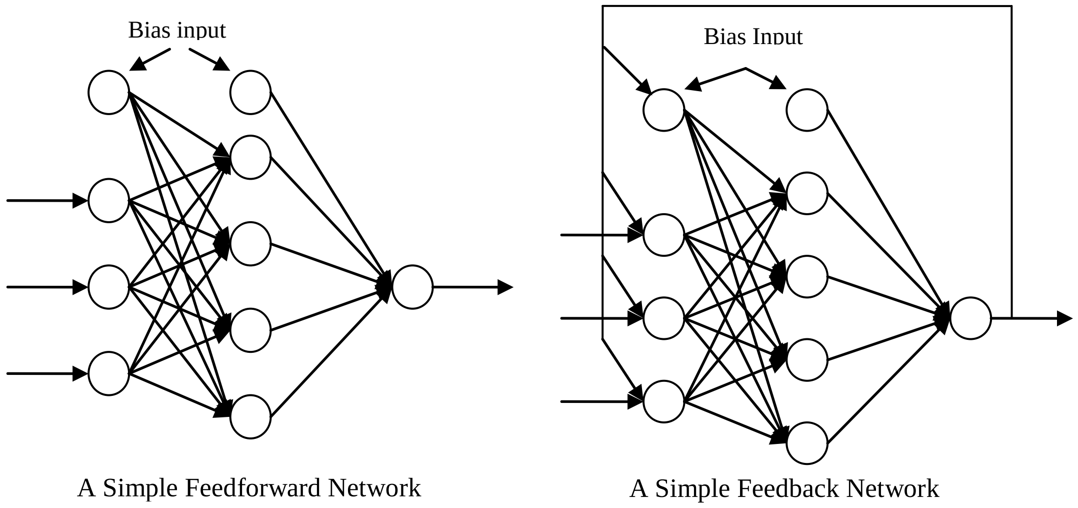


Figure 4-7: A Simple Feedforward and Feedback Network (Mesbahi, 2003)

4.4.3. Design of an Artificial Neural Networks Model

The software package NeuroSolutions5 was used to develop the artificial neural network model for the full system of LNG carrier components. NeuroSolutions5 is a graphical software program which combines a modular design interface with advanced learning procedures. This gives a flexible design approach and provides the best solution for a given problem (NeuroSolutions, 2010).

A main feature of NeuroSolutions5 is that it uses the Microsoft Excel software to perform all tasks. This includes getting data into and out of the neural network. Among the results that are presented are the regression (r) and the mean square error (MSE).

There are no defined rules to select the specific ANN architecture for a particular set of data and such a selection depends on the user. Initial results from a given method may be compared in order to choose and adjust the ANN structure. Fortunately, there are only three main steps to be followed in order to conduct the ANN training and testing stages for any internal structure of ANN. These steps are identification, training and testing, and result assessment as illustrated in Figure 4-8.

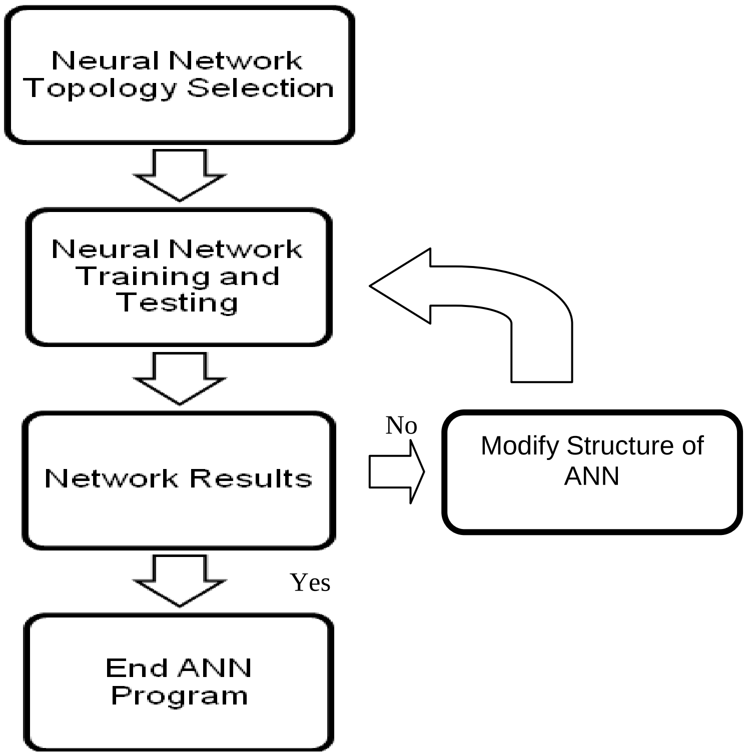


Figure 4-8: Flow Diagram for the Development of an Artificial Neural Network Model

4.4.4. The Neural Network Topology

Artificial neural networks require the user to identify the sets of inputs and associated output data for the program. In this study, the simulation data discussed in Section 4.3 was used. However, before the identification step could take place, the whole set of simulation data had to be randomised. This was to ensure equal chance for all of the data to be used for training. The number of rows of data to be used for training, cross validation and testing also needed to be identified. In this study, for the identification process, 20 rows of data were assigned for testing, 100 rows of data for cross validation and the rest of the data (51,720) for training (out of the total of 51,840). Samples of data that has been randomised and identified are shown in Table 4-8. The light and darker blue columns represent input and target output variables respectively.

Table 4-8: Sample of Randomised and Identified Data

Type of Carrier Class & Engines	Amount of LNG in the Contract (m) m3	No of Years need to deliver (year)	Round trip Distance (Nm)	Carrier Speed (knots)	Containment Systems	Type of Reliquefaction Plant	No of Propeller	Fleet size	Capital Cost/ Carrier USD (m)	Operation Cost/ Carrier USD (m)	CO_2 mass of Pollutant Emission (tonne/hr)	SOx mass of Pollutant Emission (tonne/hr)	NOx mass of Pollutant Emission (tonne/hr)
9	2.5	25	15000	23	5	3	2	67.08	47.05	30.14	26.28	0.16	0.33
19	3.5	20	10000	23	8	3	1	38.23	48.60	48.93	43.67	0.27	0.55
20	1.5	20	15000	21	7	4	1	26.37	29.29	55.60	36.82	0.23	0.46
17	3.5	20	10000	21	5	3	2	49.62	36.80	46.35	31.04	0.19	0.39
10	4.5	25	5000	19	7	3	1	51.28	22.20	19.10	17.21	0.11	0.22
14	2.5	25	5000	19	6	4	1	22.79	20.18	30.21	20.92	0.13	0.26
17	3.5	15	5000	21	8	4	2	34.67	35.60	43.96	31.04	0.19	0.39
10	0.5	25	10000	21	6	3	1	9.92	24.33	26.98	23.72	0.15	0.30
19	5.5	25	10000	21	6	4	2	52.40	29.80	36.29	31.83	0.20	0.40
19	0.5	25	5000	17	7	3	2	3.03	24.07	19.32	16.85	0.11	0.21
13	4.5	20	10000	15	8	4	2	123.33	25.55	10.53	8.71	0.05	0.11
12	4.5	15	10000	23	8	3	2	109.23	51.64	32.01	28.54	0.18	0.36
9	1.5	25	5000	17	7	3	2	18.94	23.99	11.53	10.03	0.06	0.13
11	1.5	15	5000	23	5	4	1	23.95	32.66	50.75	36.31	0.23	0.45
14	0.5	15	15000	15	6	4	2	27.09	15.94	15.57	9.78	0.06	0.12
11	3.5	20	10000	23	8	3	2	79.65	32.28	48.91	33.35	0.21	0.42
10	2.5	15	5000	21	5	4	2	43.34	30.23	23.80	21.81	0.14	0.27
10	1.5	20	5000	17	8	4	1	23.67	26.02	13.90	12.32	0.08	0.15
18	1.5	25	15000	17	8	4	1	25.90	42.22	18.20	15.31	0.10	0.19
12	5.5	20	5000	15	7	3	1	77.99	22.54	9.79	8.25	0.05	0.10

4.4.5. The Artificial Neural Network Training Process

The next step was the 'training' of the data, in which the network topology was selected and the activation function and the number of epochs needed to be confirmed. A multilayer perception network topology was used for this study and its architecture is illustrated in Figure 4-9.

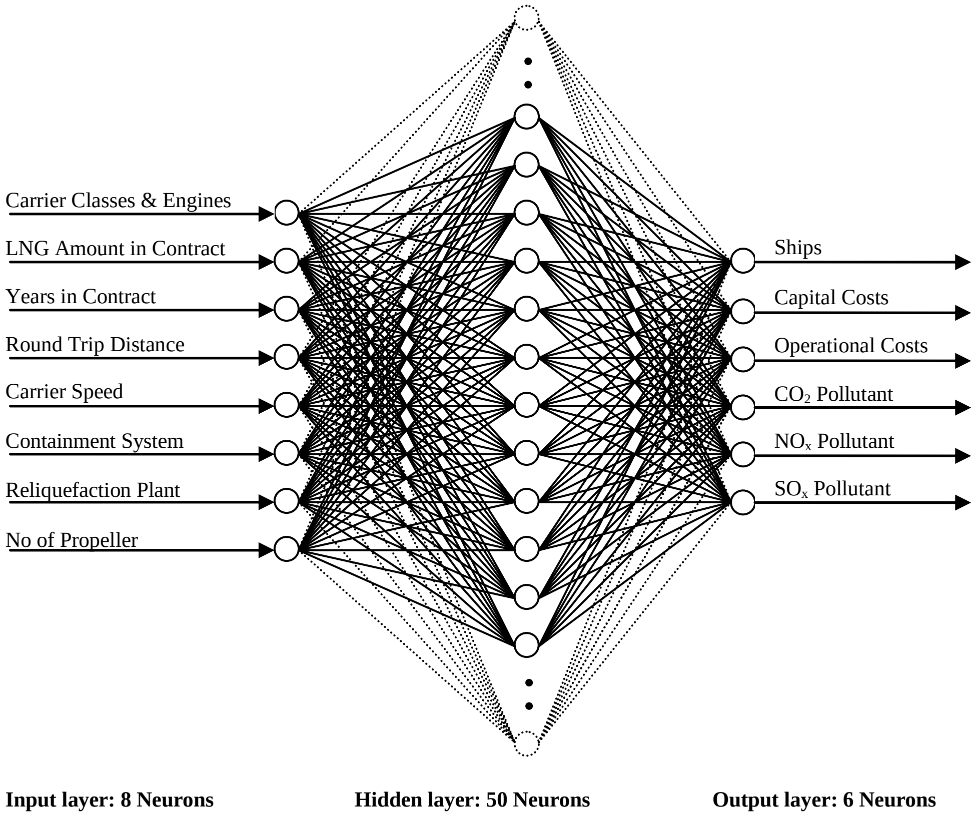


Figure 4-9: Three Layer Feed Forward Neural Network Topology Used

The first layer, which is the input layer, consists of eight neurons representing the LNG carrier components and independent variables that have been assessed to have a high impact on the outcome of the study. Meanwhile, the second layer is the hidden layer. There are no strict rules applied to determine the optimum number of hidden layers and the number of processing elements on that layer. A configuration of three layers and 50 processing elements was selected based on a number of simulation investigations.

Both of the popular non-linear activation functions, namely the sigmoid and Tanh were used during the training process. The better of the two, based on performance, was then selected for the testing process as discussed in the following section.

Epochs represent the number of iterations required to reach convergence and in this study, the trial number of epochs was set at 1000.

4.4.6. The Neural Network Training Results

As mentioned earlier, the accuracy of the results from an ANN is highly dependent on the quantity of data that needs to be trained. In addition, all of the inputs should be independent variables including the full range of characteristics needed to build the relationships with the outputs. This is important for the network to be able to fully learn the relationships. During the training process, the input and the desired output data are repeatedly presented to the network. As the network continuously strives to learn the relationships between the inputs and the outputs, the 'weights' of the system are constantly adjusted in order to reduce the gap between the current outputs and the desired target response. This instantaneous gap can be represented by the mean square error (MSE) which is the average of the difference between each consecutive output of the processing elements and the desired output:

$$MSE = \frac{\sum_{j=0}^{P}\sum_{i=0}^{N}(d_{ij} - y_{ij})}{N \cdot P}$$

Equation 4-2: Mean Square Error

Where:

P is the number of output processing elements

N is the number of exemplars in the data

d_{ij} is the desired output for exemplar i at processing j

y_{ij} is the network output for exemplar i at processing j

The alternative training results, using the sigmoid and Tanh activation functions, are shown in Figure 4-10and Figure 4-11respectively.

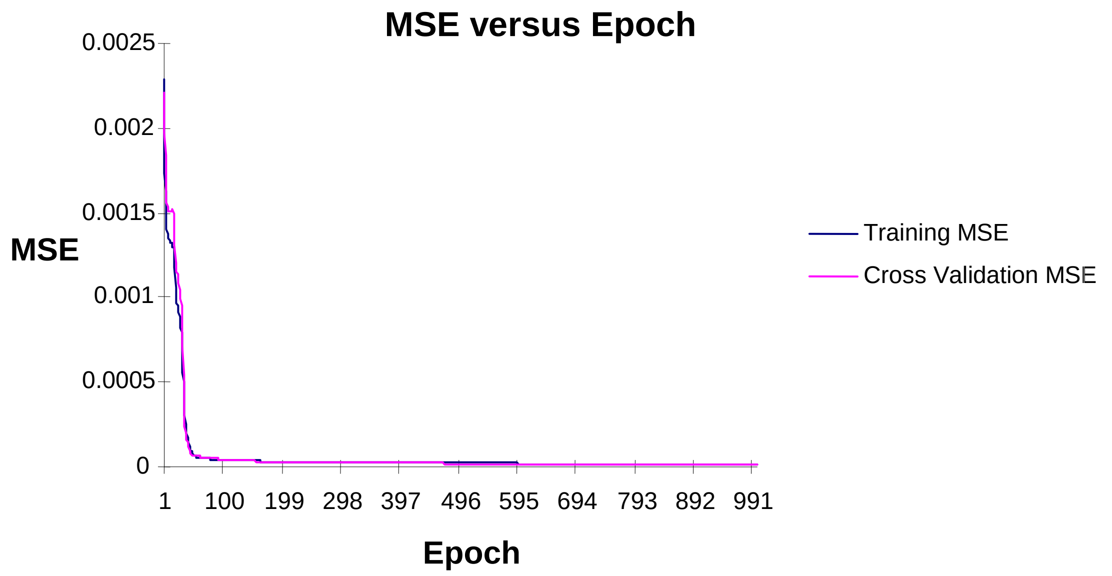


Figure 4-10: Training Result of the Data using the Sigmoid Function

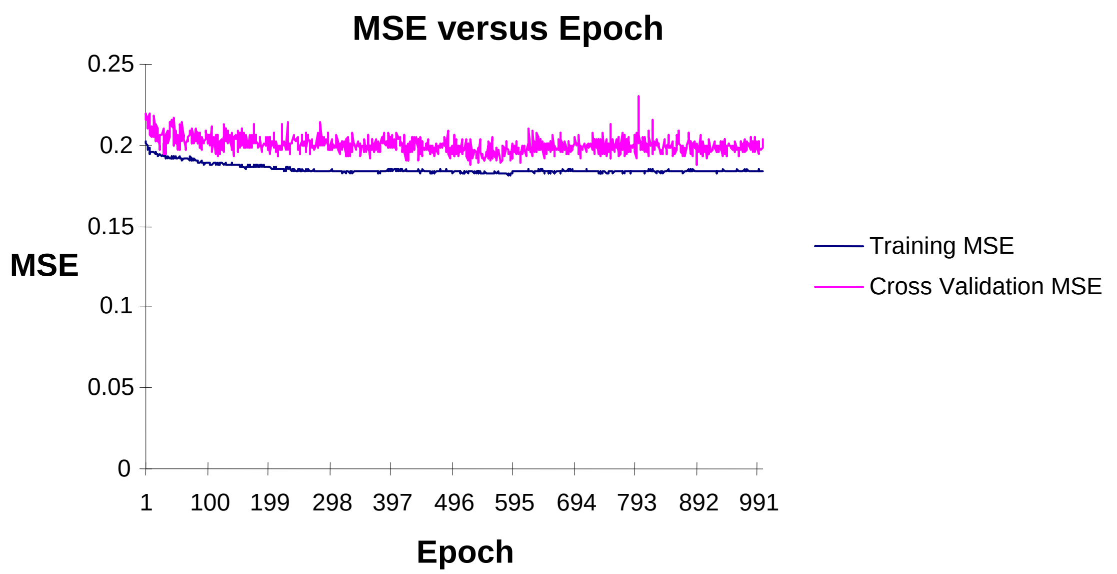


Figure 4-11: Training Result of the Data using the Tanh Function

The results indicate that the sigmoid activation function has a relatively small MSE, which is a measure of the accuracy of ANN output vs. desired output data. In fact, after approximately 170 iterations (epochs), the average MSE is almost constant and close to zero. Therefore the sigmoid activation function was chosen for the rest of this study.

4.4.7. The Artificial Neural Network Testing and Results

Once the ANN has been trained, the next step is to test the trained network with sets of data, both input and output, that have not already been seen. During the testing stage, the results were compared with the MSE, to determine the degree to which the desired results conformed to the actual output results. However, this does not indicate whether the two sets of data are approaching from the same direction. The regression (*r*), or correlation coefficient, can be used to solve this problem. The regression coefficient can be expressed by:

$$r = \frac{\dfrac{\sum_i (y_i - y)(d_i - d)}{N}}{\sqrt{\dfrac{\sum_i (d_i - d)^2}{N}}\sqrt{\dfrac{\sum_i (y_i - y)^2}{N}}}$$

Equation 4-3: Regression Coefficient

Where:

y is the data output

d is the desired output

i is exemplar

N is the number of exemplars in the data

This regression coefficient lies between plus one and minus one. If the coefficient is plus one, there is a perfect positive relationship between *y* and *d*, and when the coefficient is minus one, there is a perfect negative relationship between them which varies in the opposite direction. The MSE and regression coefficient of the training data are illustrated in Table 4-9. The test performances have shown accurate results because all the outputs have minimum MSE and *r* values that are approximately one (more than 0.99).

Table 4-9: The Performance of Trained ANN with Test Data

Performance	Fleet size	Capital Cost/ Carrier USD (m)	Operation Cost/ Carrier USD (m)	CO_2 mass of Pollutant Emission (tonne/hr)	NO_x mass of Pollutant Emission (tonne/hr)	SO_x mass of Pollutant Emission (tonne/hr)
MSE	4.588	0.303	0.316	0.023	9.936×10^7	3.457×10^6
r	0.999	0.998	0.999	0.999	0.999	0.999

A sample of the ANN testing results is shown in Table 4-10. The blue columns are the actual output data and the green columns are the desired output data. This data is based on 20 rows of randomised inputs, and the graphical representation of the results is illustrated in Figure 4-12.

Table 4-10: Example of the ANN Testing Results

Fleet size	Capital Cost/ Carrier USD (m)	Operation Cost/ Carrier USD (m)	CO2 mass of Pollutant Emission (tonne/hr)	NOx mass of Pollutant Emission (tonne/hr)	SOx mass of Pollutant Emission (tonne/hr)	No of Fleet Output	Capital Cost/ Carrier USD (m) Output	Operation Cost/ Carrier USD (m) Output	CO2 mass of Pollutant Emission (tonne/hr) Output	SOx mass of Pollutant Emission (tonne/hr) Output	NOx mass of Pollutant Emission (tonne/hr) Output
54.60	23.36	23.56	20.26	0.13	0.25	54.97	23.47	23.33	20.19	0.13	0.25
18.27	24.73	15.25	9.78	0.06	0.12	21.76	24.03	13.83	9.49	0.06	0.12
142.04	30.07	20.28	17.36	0.11	0.22	142.72	29.73	20.01	17.18	0.11	0.21
23.82	45.50	32.16	28.16	0.18	0.35	22.84	46.50	32.62	28.10	0.18	0.35
52.69	28.84	34.51	32.35	0.20	0.40	52.41	29.07	34.59	32.34	0.20	0.40
145.26	35.18	17.93	15.22	0.10	0.19	145.96	35.43	17.80	15.12	0.09	0.19
44.77	33.85	20.01	17.92	0.11	0.22	43.21	33.32	19.76	17.82	0.11	0.22
5.43	21.44	33.01	22.74	0.14	0.28	6.15	22.04	32.83	22.66	0.14	0.28
87.46	22.67	29.86	19.43	0.12	0.24	87.42	22.94	29.66	19.35	0.12	0.24
106.20	40.15	29.56	26.28	0.16	0.33	105.69	39.89	29.41	26.23	0.16	0.33
113.38	26.35	21.40	14.03	0.09	0.18	116.07	26.33	20.04	13.77	0.09	0.17
212.85	19.93	12.63	10.18	0.06	0.13	219.78	20.77	13.03	10.03	0.06	0.13
5.67	18.33	20.65	13.56	0.09	0.17	5.36	19.38	20.60	13.65	0.09	0.17
58.05	24.62	11.59	9.32	0.06	0.12	57.20	24.36	11.84	9.57	0.06	0.12
5.96	58.87	33.19	29.01	0.18	0.36	4.91	59.00	33.48	28.87	0.18	0.36
175.78	31.96	43.27	28.77	0.18	0.36	172.16	31.81	44.15	28.95	0.18	0.36
64.56	29.91	19.37	16.48	0.10	0.21	63.07	28.91	18.84	16.30	0.10	0.20
14.65	34.39	29.49	25.63	0.16	0.32	15.29	33.98	29.14	25.69	0.16	0.32
111.65	29.72	39.38	26.63	0.17	0.33	112.71	29.36	39.96	26.81	0.17	0.33
150.93	32.28	49.77	33.35	0.21	0.42	151.36	31.71	49.39	33.22	0.21	0.42

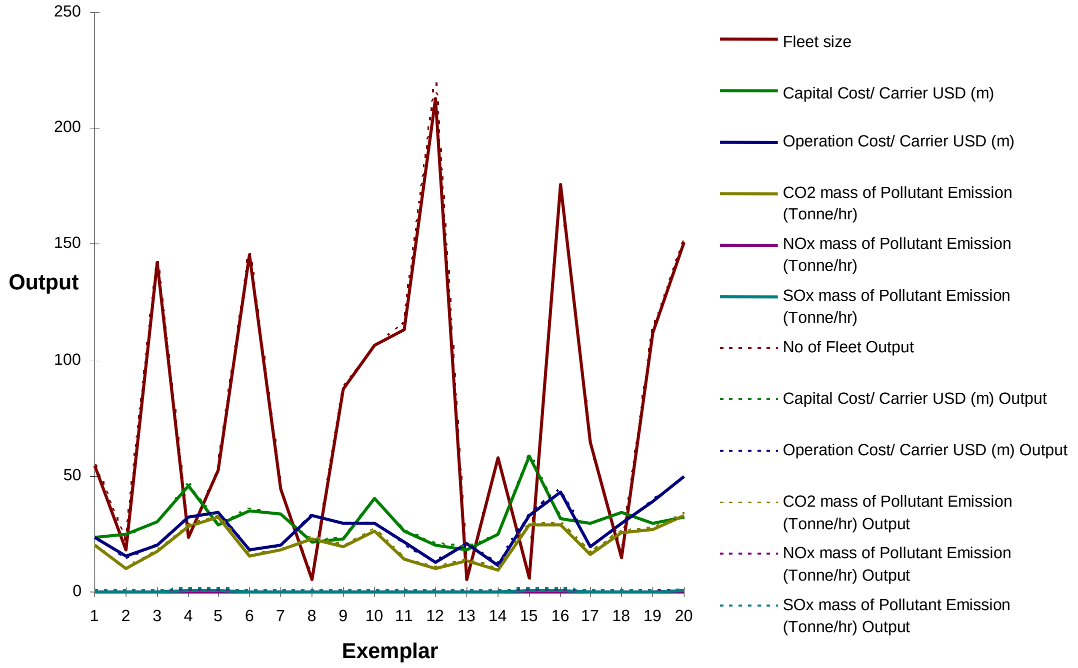


Figure 4-12: Desired Output and Actual Network Output Testing Data Results

The two main aims of using the ANN software were to reduce the decision area and to minimise the computation time. The results produced by the ANN model are close to those obtained from the full model, however for higher accuracy; the results could then be fed back into the simulation model. Doing so would improve the speed of processing and the accuracy of the results from the simulation model.

4.5. Chapter Summary

The purpose of this chapter was to develop a simulation model, generate simulation data and then develop a simplified model of the overall LNG carrier system. The development of the simulation model was carried out in two steps. Step one translated all the components of an LNG carrier into mathematical models, while step two linked these components together using a single piece of software.

The translation to a mathematical model required detailed investigation of the behaviour of the components and the main challenge was to consider and adapt all the possible constraints within each component. Furthermore, selecting the correct equation was crucial. There were a total of six groups of components/systems which needed to be transformed into mathematical models. They were (1) the containment system, (2) the reliquefaction plant, (3) the power prediction, (4) the life cycle cost analysis, (5) the emission of pollution products from the selected engine, and (6) the ship steel weight. Details of the model developments are provided in the appendices. Once the formulation for each of the components had been achieved, the construction of the simulation model was carried out using the LabVIEW software.

Collecting simulation data from the simulation model required three steps: (1) selecting the variables; (2) setting the range and increment; and (3) systematically feeding the input into the simulation model. Due to the large simulation data set produced, an Artificial Neural Network was trained with the data in order to reduce computational time without reducing the quality of the information. The background of this software has being explained as well as its advantages and limitations. Using the ANN model, the trend or pattern of the results is based on changing the input variables being studied and analysed.

This model was then applied to find the optimal combination of LNG carrier components according to the stated aims of this study. This was achieved by creating another simulation programme which analysed the contributions of each component to determine their minimum values given the set of objectives. The whole process is referred to as the ‘decision making technique’ and details are explained and discussed in the next chapter.

5. Decision Making Support Technique

Objectives

The overall aim of this chapter is to discuss a methodology for a preliminary decision making technique for the design of a new LNG carrier.

The objectives of this chapter are thus summarised as follows:

- To describe the criteria for the technique inputs.
- To develop the decision making technique.
- To analyse the results obtained for selected cases.

5.1. Introduction

The overall aim of this study was to develop a holistic ship design methodology which could produce the best possible combination of an LNG carrier’s main components to comply with an objective function for application at the preliminary stage. At this stage, major decisions are made that affect the overall configuration of a vessel, including the selection of the major components and systems that have a significant effect on both the capital and operational costs. As developments cycle through the phases of increasing design definition, it becomes progressively more difficult to make changes to the major components and systems without incurring serious slippages to the build schedule and increases to the manufacturing costs. This methodology is an approach to reduce the life time costs of LNG carriers from the preliminary design stage to the point when the ship is eventually sold or scrapped. The objective function for ships varies according to their purpose and priority throughout their life span. For example, for a passenger ship the main priority is to ensure the safety and comfort of the passengers throughout the journey. For an LNG carrier, the main purpose is to transport the LNG safely between two agreed companies with the minimum fleet size, capital and operational costs, and pollutant emissions whilst operating according to the international rules and regulations.

5.2. Decision Making Process

The decision making technique employed for the LNG carrier in this study was based on the ANN model introduced in the previous chapter. This technique was designed to handle multi objective functions. Although this proposed technique produces recommended solutions at the end of the process, the final decision of selecting the actual components would still remain within the ship-owner's exclusive power. This proposed decision making technique is thus a support tool for the ship-owner to aid him in selecting the final combination of the main components.

Figure 5-1 illustrates the complexity of the decision making process for an LNG carrier. Once the trading requirement is known, the process for selecting the main components of an LNG carrier may be started. Since LNG carrier components are interrelated, all of the possible combinations of the components and their interactions need to be considered. Results were recorded for each of the combinations based on the objective function. The minimum or maximum values of the results that were recorded were then identified. This combination of components was then the optimal combination or a close to optimal combination to satisfy a given objective function. The decision making process is complex and best handled through the use of a simulation programme. In order to achieve this, a mathematical representation of the decision making was required.

Before creating the mathematical model an understanding of the entire inter-related process including its limitations was necessary. In this study, the decision making process involved many local and overall targets, and hence it required a technique that was capable of handling many conflicting criteria with complex interrelationships.

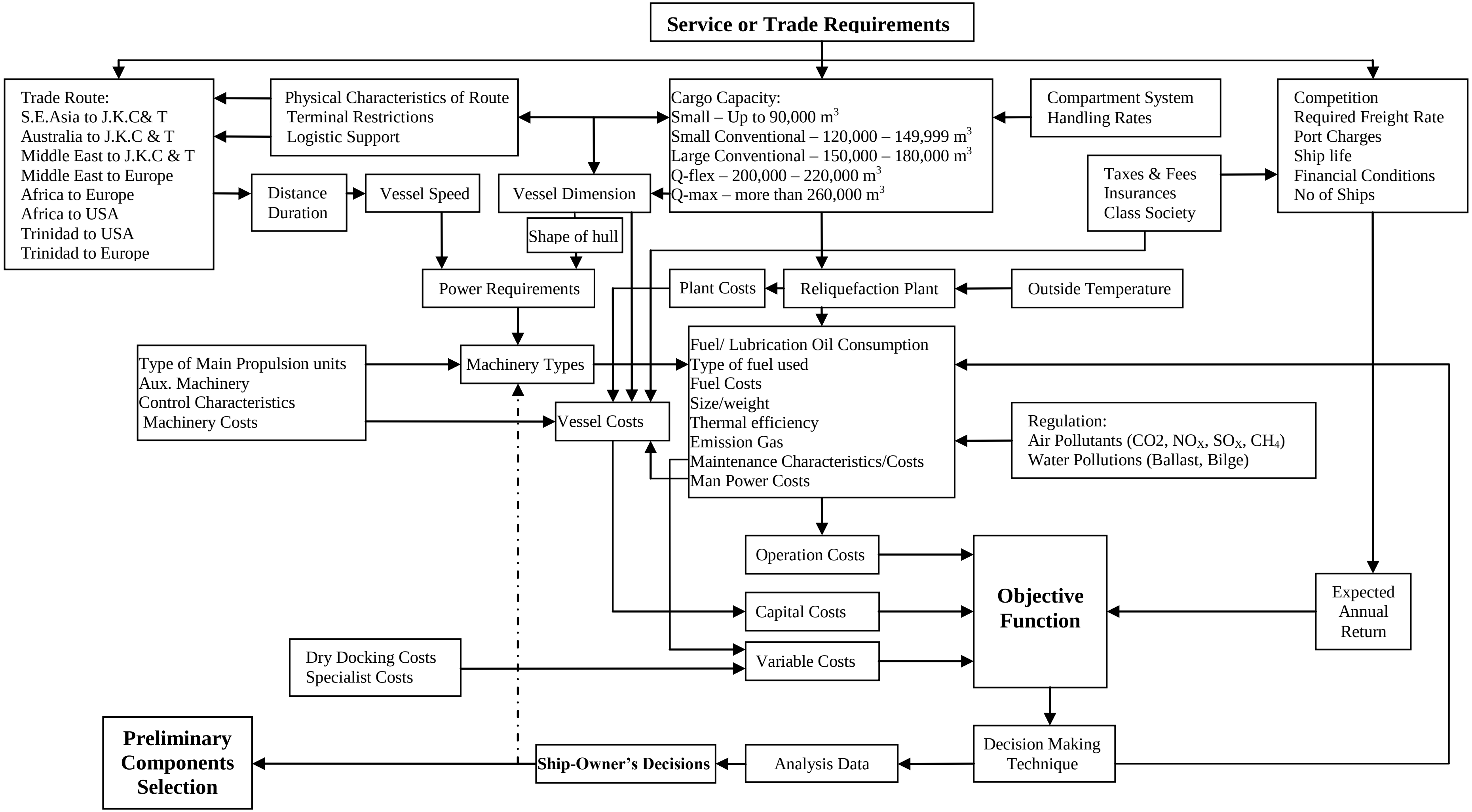


Figure 5-1: Decision Making process for Selecting Preliminary Components

Note: J.K.C. &T is referring to Japan, Korea, China and Taiwan.

The mathematical form of this multi-decision making technique can be written as:

$$f(X) = \sum \alpha_n f_n(x)$$

Equation 5-1: Multi-objective Decision Making Equation

Where:

$f(X)$ is the overall objective function,

$f_n(x)$ are two or more conflicting objective functions,

α_n are constant 'weight' values which indicate the relative importance of one objective function compared to the other.

Example of a typical real case scenario

A route between Malaysia (Bintulu) and Japan (Tokyo) used for LNG transportation was selected, as shown in Figure 5-2. The round trip distance is approximately 5000 nautical miles and the contract is between PETRONAS and Tokyo Gas.

Figure 5-2: Map illustrating the Route between Malaysia and Japan

One of the carriers which are currently in service transporting LNG under this contract is the SS Puteri Delima. The details on this carrier are:

Ship-owner:	M.I.S.C.	Delivery:	Jan-95
Shipbuilder:	Atlantique	Flag:	Malaysia
Build in:	France	Class:	LR
Contract:	1991	Horse Power:	36,300 (~ 27 MW)

The comparison between the actual service carrier and author-proposed software is shown in Table 5-1:

Table 5-1: Comparison between Actual Service carrier and Proposed Software

Components	**SS Puteri Delima**	**Proposed software**
Size of the carrier	Small Conventional	Q-flex
Type of engine	Steam Turbine	Slow Speed ICE
Speed (knots)	21	15
Containment System	No 96	MARK III
Reliquefaction Plant	-	Cryostar
No. of Propeller	Single	Twin

It is clear that all the components are different in the two cases. There are many possible reasons for the real carrier having the combination that it has, such as; the vessel was designed for use over another totally different route or ship-owner decision. The proposed technique is intended to reduce the total costs for LNG transportation for this specific route and the amount of cargo to be delivered; hence it proposes the combination of components that best achieves this objective. The selected components comply with the discussion explained in Chapter Three. Thus it can be shown to determine the components correctly and it is able to produce the results almost instantaneously. This programme was created by using the LabVIEW software and is shown in functional form in Figure 5-3.

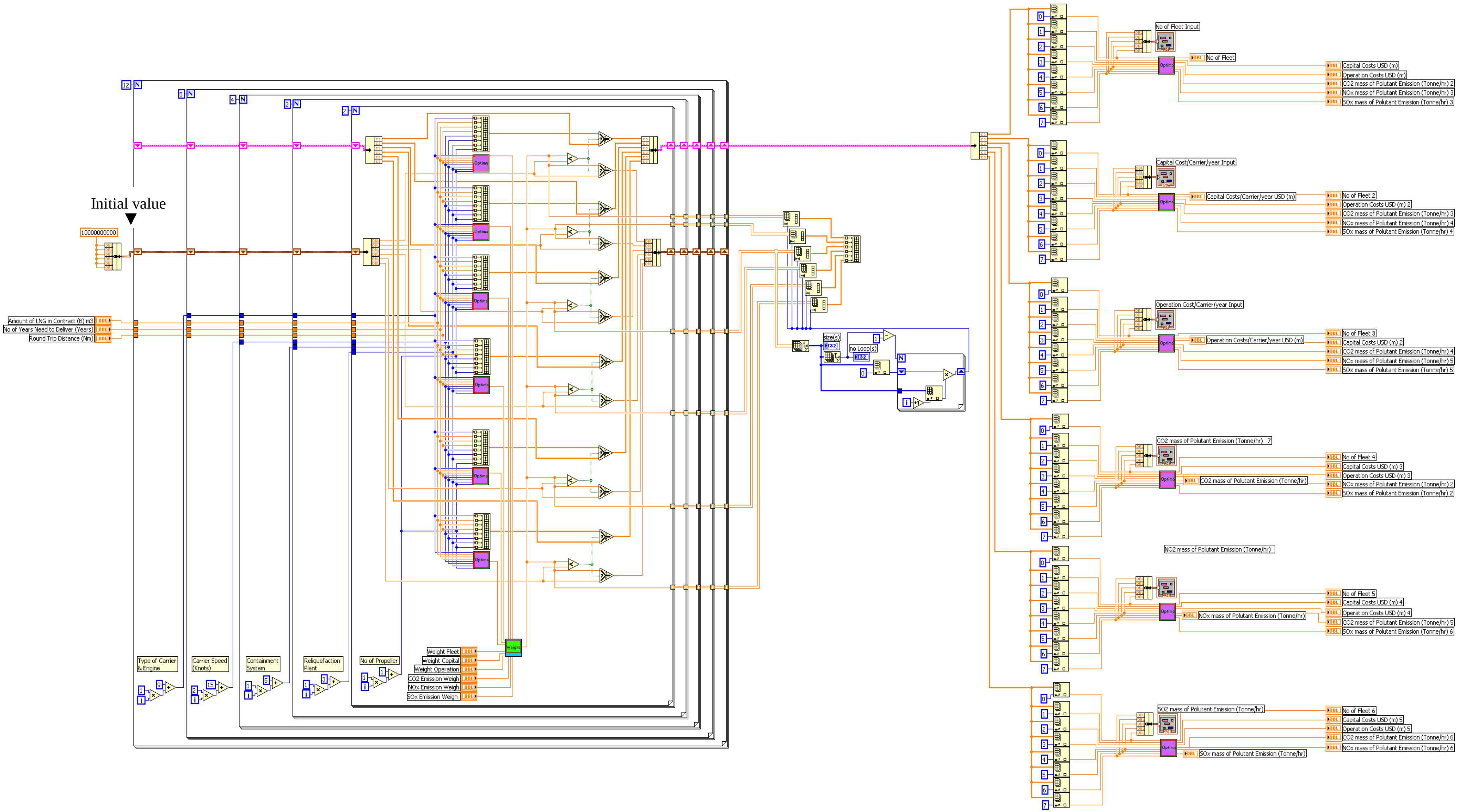


Figure 5-3: Simulation Programme for the evolved Decision Making Technique

A simplified way to help to explain Figure 5-3 is by using a flow chart as illustrated in Figure 5-4.

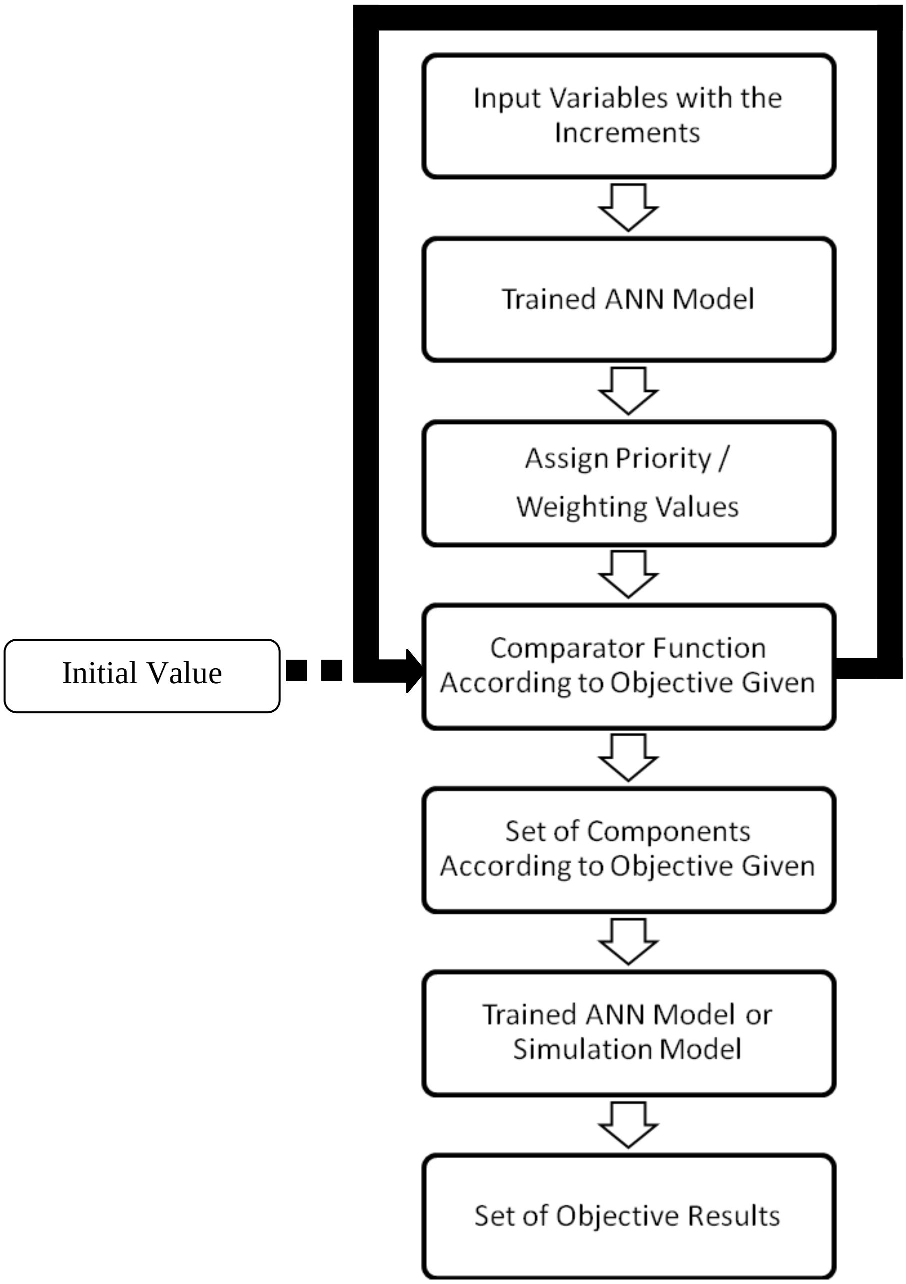


Figure 5-4: Multi-objective Decision Making Process Flow

A large initial value is input to act as a dummy value for comparison purposes. When the program is started and runs, each result from the corresponding Artificial Neural Networks (ANN) model is compared with this large dummy number. The ANN model is represented in Figure 5-3 by a purple box marked ‘optima’.

Results for each criterion were then multiplied by a constant weight in order to produce a 'current value' which was then compared with the initial value and the lower of the two was recorded temporarily before being compared again following the next iteration loop. The iteration process was continued until the specified number of loops was completed.

A set of minimum values was transferred and then extracted in order to show the particular combination of the various components. Since the product value from the assigned weight process was the same for all the comparators, the resulting value was similar for all the criteria. The assignment of 'weight' also enables the user to select a value for a specific measure in order to enable the user to impose some bias, as opposed to setting all parameters to be of the same importance. These sets of values were then fed back to the trained ANN model, or the simulation model, in order to obtain a set of objective results. The comparison between the trained ANN model results and the simulation model results is shown in table 5-2 for the six selected criteria.

Table 5-2: Comparison between ANN trained and Simulation models

Outputs	**ANN Trained Model**	**Simulation Model**	**Percentage Error**
Results			
No. of Ships	23.6	24.53	**3.79**
	The values based on a single ship		
Capital Cost (m) USD	21.45	22.45	**4.45**
Operational Cost (m) USD/year	10.89	11.40	**4.47**
CO_2 mass of Pollutant Emission (Tonne/hr)	8.961	9.005	**0.49**
SOx mass of Pollutant Emission (Tonne/hr)	0.224	0.225	**0.44**
NOx mass of Pollutant Emission (Tonne/hr)	0.112	0.113	**0.88**

The maximum percentage error between models was less than 5%, which showed the relative accuracy of the ANN trained model results. Although the results from the ANN model are close to those obtained from the full simulation model, they can be improved by feeding them back into the simulation model to obtain more accurate results. Doing so will improve the speed of the overall processing and the accuracy of the final results.

This program produces two sets of results simultaneously, which are:

1. A prescriptive combination set of the specific component values that produced the minimum values of each of the given six criteria, and
2. A set of results produced from the above prescriptive combination of values of the components as given above for each criterion.

The following sections explain in detail each process within this technique.

5.2.1. Program Development

The most crucial element in developing a decision making technique is to select or formulate accurately the objective function for solving the given problem. In this study the selected objective functions are:

1. Minimum number of identical ships in the fleet.
2. Minimum capital cost for the ship.
3. Minimum operational cost per year for a ship.
4. Minimum mass of CO_2 pollutant emissions for the ship per unit of time.
5. Minimum mass of SO_x pollutant emissions for the ship per unit of time.
6. Minimum mass of NO_x pollutant emissions for the ship per unit of time.

The next step was to identify the selected inputs which represent all of the main components of the LNG carrier. These are:

1. The amount or volume of LNG to be delivered by the fleet over a given period of time.
2. The time duration scheduled in which to deliver the full amount of cargo according to the contract.
3. The round trip distance between the export and import terminals.
4. The carrier's required service speed.
5. The number of propellers, which indicates the hull form to be constructed.
6. The type of containment system to be selected.
7. The type of reliquefaction plant to be chosen.
8. The LNG carrier classes and engines to be selected.

The first three of these variables are fixed, because they are bound by the terms of the contract agreed between exporter and importer. The rest of the components are variables to be selected by the ship-owner in order to produce the minimums of fleet size, overall capital and operational costs, and overall pollutant emission products. A summary of the variables of the components complete with their allowed ranges or selectable options is illustrated in
Table **5-3**.

Table 5-3: Complete variables with their Ranges and Items

Inputs	Ranges/Items
Volume of the LNG (B) m^3	Fixed
Delivery duration (Years)	Fixed
Round trip distance (Nm)	Fixed
Speed (Knots)	15 - 23
No of Propellers	Single Propeller
	Twin Propeller
Type of Reliquefaction Plant	Hamworthy Reliquefaction Plant
	Cryostar Reliquefaction Plant
Type of Containment System	No96 Containment System
	MARK III Containment System
	CS1 Containment System
	MOSS Containment System
LNG Carrier Classes & Associated Engines	Small Conventional & Slow Speed Engine
	Small Conventional & Medium Speed Engine
	Small Conventional & Gas Turbine
	Large Conventional & Slow Speed Engine
	Large Conventional & Medium Speed Engine
	Large Conventional & Gas Turbine
	Q-flex & Slow Speed Engine
	Q-flex & Medium Speed Engine
	Q-flex & Gas Turbine
	Q-Max & Slow Speed Engine
	Q-Max & Medium Speed Engine
	Q-Max & Gas Turbine

Initial values for the variables need to be established. Without these starting values, the simulation programme cannot be operated because the computer needs to have indicated to it which values need to be calculated.

In the case of the 'type' of components, they must be represented in number form, and this applies also for their allowable increments. The initial values, increments and the number of iterations of these variables are shown in Table 5-4.

Table 5-4: Initial Value/ type of components, Increments and Number of Iterations for the Input Variables

Independent Variables	Initial Values/ type of components	Increments	No of Iterations/ loops
Ship Speed (Knots)	15	2	5
No of Propellers	**1**	1	2
Type of Reliquefaction Plant	**3**	1	2
Type of Containment System	**5**	1	4
LNG Carrier Classes & Engine	**9**	1	12

Note: The dark blue numbers in the cells represent the input components as identified earlier in Table 4-7.

The following section discusses the selected case studies and the results of using the proposed decision making technique.

5.3. Case Studies

Three case studies were undertaken in order to investigate the performance of the multi-objective decision making technique. These studies are:

- Case study 1: Transporting LNG from Malaysia (Bintulu) to Japan (Tokyo). A round trip voyage distance of approximately 5,000 nautical miles,
- Case study 2: Transporting LNG from Qatar (Doha) to Europe (Netherlands-Rotterdam). A round trip voyage distance of approximately 12,620 nautical miles, and
- Case study 3: Transporting LNG from Russia (St. Petersburg) to Europe (Italy-Bari). A round trip voyage distance of approximately 7,420 nautical miles.

In order to remain consistent and for ease of illustration and comparison, some of the operating values have been fixed in the case study calculations. These are:

- Amount of LNG in the contract: 1 billion m^3,
- Number of years in contract: 20 years, and
- Pollutant Emission Ratio (PER) for the following compositions were taken as (Woud and Stapersma, 2002):
    - CO_2 (86 % C in fuel) : 3200 g/kg of fuel,
    - NO_x : 40 g/kg of fuel,
    - SO_x (4 % S in fuel) : 80 g/kg of fuel – High Sulphur content
    - SO_x (1 % S in fuel) : 20 g/kg of fuel – Low Sulphur content

The aim of the case studies was to generate and then to evaluate the results obtained from the multi-objective decision making calculations and to determine the optimal combination of the various main components of the vessels for each of the selected routes. With regard to the introduction of Sulphur oxide Emission Control Areas (SECA), which have been enforced within the North Sea as defined by regulation 5(1)(f) of MARPOL Annex V since March 2010, the aim is also to ensure that the study is up to date in relation to industry issues. Implementing the SECA rules and regulations requires some modifications to the equipment and operation of the vessel which will inevitably have impacts on the overall cost of LNG carriers.

In order to study the effects of the SECA area requirements on the case studies, two sets of scenarios were investigated in which operations both outside and inside the SECA was carried out (case study 2 and 3).

- **Outside SECA Regulation Areas**

Heavy fuel oil (HFO) is the most common fuel that is used for merchant ships worldwide due to its relatively low cost. It basically consists of residual refinery products and has a density greater than 1000 kg/m^3 (Concawe, 1998).

It has, however, environmental implications, not only from the composition of the exhaust gases but also with respect to the sea water in the case of potential spillages due to accidents, carelessness, grounding or collisions. Table 5-5 shows the multi-objective decision making results for an LNG carrier using standard HFO (high sulphur) for the three different case studies.

Table 5-5: Results from the Multi-Objective Decision making analysis for three standard Fuel Case Studies

Outputs/Inputs	**Case Study 1: Malaysia (Bintulu) to Japan (Tokyo)**	**Case Study 2: Qatar (Doha) to Europe (Netherland - Rotterdam)**	**Case Study 3: Russia (St Petersburg) to Europe (Italy – Bari)**
Results			
No. of Ships in fleet	14.18	24.53	20.58
	The following values based on a single ship		
Capital Cost (m) USD	20.49	22.45	20.49
Operational Cost (m) USD/year	9.377	11.400	9.567
CO_2 mass of Pollutant Emission (Tonne/hr)	7.703	9.005	7.703
SOx mass of Pollutant Emission (Tonne/hr)	0.193	0.225	0.193
NOx mass of Pollutant Emission (Tonne/hr)	0.096	0.113	0.096
LNG carrier Components			
Amount of LNG in Contract (B) m^3	**1**	**1**	**1**
Number of Years in Contract	**20**	**20**	**20**
Round Trip Distance (Nm)	**5000**	**12620**	**7420**
Number of Propellers	2	2	2
Type of Reliquefaction Plants	4	4	4
Type of Containment System	6	6	6
Vessel Speed	15	15	15
Type of Carrier and Engine	12	15	12

As shown in table 5-5, the generated optimal LNG carrier components for the three case studies are very similar except in the selection of the size and cargo capacity of the ship. In Case Study 2, the Q-flex size was selected (highlighted in yellow) while for the other two a Large Conventional vessel was selected.

From the results produced, the sizes of the fleets were seen to be different between the case studies and mainly this was due to the different round-trip distances involved, although the same combination of components are used in Case Studies 1 and 3.

In terms of the capital cost, Case Studies 1 and 3 produced the same result because they have the same components, whereas in Case Study 2, as the size of the ship increases, the cost of construction of the ship also increases. In addition, the higher power requirement increases the main engine costs. Hence, the capital cost in Case Study 2 is the highest.

As for the operational costs, all of the case studies have different values due to the difference in fleet size. If the fleet size and the components are the same, the operational costs should also have similar values. This situation will also apply to the mass of the pollutant products.

- **Within the SECA Regulations sea Area**

The regulations for the Sulphur Oxide (SO_x) emission control areas (SECA) are part of the MARPOL Annex VI: Regulations for the Prevention of Air Pollution. Particularly, Chapter Three, regulation 14(3) which mentions the requirements for controlling the exhaust gas emissions from ships. In order to comply with the regulation, there are two on-board options which can be implemented:

1. Using an approved exhaust gas cleaning process, also known as a 'scrubber',

or

2. Using low sulphur HFO on board ships which has a content of less than 1.5 percent of sulphur by mass.

The following sub-sections illustrate the consequences of these options.

Option One – Using Standard Fuel with Scrubber

A scrubber is a piece of equipment that can 'clean', in a continuous process the main engine exhaust gas in order to reduce the SO_x present before the remaining exhaust gas is released into the atmosphere. It works by spraying a solution of sodium hydroxide in solution in water into the exhaust gas and then allowing it to pass through a demister via an absorption section. In the absorption section, the treated exhaust gas slowly flows upwards in a direction that is in contra flow to the water. The demister holds any water droplets from within the gas and the cleaned exhaust gas is then heated before it is released into the funnel in order to prevent local condensation and thus a visible vapour from occurring. The relationship between the sulphur content in the fuel and the level of sodium hydroxide in the water determines the level of reduction of the SO_x (PIN, 2008).

Table 5-6 contains the results from the multi-objective decision making process for an LNG carrier using standard fuel with a scrubber installed. From this table, the combination of components identified for Case Study 2 was significantly different from those for the other two case studies in both the type of reliquefaction plant and the ship size. The multi-objective decision making identified in this situation the Cryostar reliquefaction plant and a small conventional size of vessel for both Case Studies 1 and 3, while the Hamworthy reliquefaction plant and the Q-flex size of the ship were again selected for Case Study 2 (highlighted in yellow).

Table 5-6: Results of Multi-Objective Decision making for Standard Fuel and Using a Scrubber on all three routes

Outputs/Inputs	**Case Study 1: Malaysia (Bintulu) to Japan (Tokyo)**	**Case Study 2: Qatar (Doha) to Europe (Netherland - Rotterdam)**	**Case Study 3: Russia (St Petersburg) to Europe (Italy – Bari)**
Results			
No. of Ships in fleet	14.18	24.53	20.58
	The following values based on a single ship		
Capital Cost (m) USD	20.99	22.95	20.99
Operational Cost (m) USD/year	9.413	11.41	9.603
CO_2 mass of Pollutant Emission (Tonne/hr)	7.703	9.005	7.703
SOx mass of Pollutant Emission (Tonne/hr)	0.196	0.225	0.193
NOx mass of Pollutant Emission (Tonne/hr)	0.096	0.113	0.096
LNG carrier Components			
Amount of LNG in Contract (B) m^3	**1**	**1**	**1**
Number of Years in Contract	**20**	**20**	**20**
Round Trip Distance (Nm)	**5000**	**12620**	**7420**
Number of Propellers	2	2	2
Type of Reliquefaction Plant	3	4	3
Type of Containment System	6	6	6
Vessel Speed	15	15	15
Type of Carrier and Engine	12	15	12

In terms of the size of the fleets, the number of carriers in each is different due to the difference in round-trip distances. As the distance increases, the fleet size also increases, as has been mentioned in chapter three under the effects of the distance on fleet size.

The scrubber unit was an additional equipment requirement for the ship and hence its cost was added into the capital costs. In practice, the cost of this unit varies with the volume of exhaust gas that is required to be processed and its manufacturer; however for convenience, in this study, the price of the scrubber was fixed at USD 500,000.00 per ship for the comparison purposes. As a result, the capital cost for this option was higher than the corresponding option of just using high sulphur fuel.

Once a scrubber has been installed onboard the ship, the power and maintenance costs for operating the scrubber need to be calculated and this cost is to be added into the operational costs. Ten thousand USD per year has been assumed in this study, and this additional cost has contributed to an increase in the operational costs for vessels otherwise using only standard fuel with similar ship components.

The purpose of the scrubber is to reduce SOx emissions; however, in Table 5-6 the SOx level does not show any obvious reduction compared to table 5-5. This is because the SOx mass in the table is a result of the exhaust gas composition calculation before entering into the scrubber. Thus the amount of SOx after the scrubber should be less than 1.5%, though the rest of the other pollutant emission products will be the same.

Option Two – Using Low Sulphur Fuel

A low sulphur fuel, as its name implies, has less sulphur in the fuel compared with the composition of the standard fuel, however it is more expensive. Table 5-7 shows the multi-objective decision making results, for the three case studies for LNG carriers using low sulphur HFO during the round trip voyage.

The low sulphur fuel would be loaded in anticipation for the ships which were to be sailing through the SECA areas, while for other sections of the routes they would burn standard fuel. The change-over process, between voyages, would require additional time, which would contribute to a reduction in the number of trips per year and would therefore potentially result in an increase in the number of carriers required in the fleet. To allow for this situation, an extra one day has been assumed each trip.

Table 5-7: Result of Multi-objective Decision making for Low Sulphur Fuel for all routes

Outputs/Inputs	**Case Study 1: Malaysia (Bintulu) to Japan (Tokyo)**	**Case Study 2: Qatar (Doha) to Europe (Netherland - Rotterdam)**	**Case Study 3: Russia (St Petersburg) to Europe (Italy – Bari)**
Results			
No. of Ships	15.13	25.21	15.38
	The following values based on a single ship		
Capital Cost (m) USD	20.49	22.45	22.45
Operational Cost (m) USD/year	9.033	11.360	10.990
CO_2 mass of Pollutant Emission (Tonne/hr)	7.703	9.005	9.005
SOx mass of Pollutant Emission (Tonne/hr)	0.048	0.056	0.056
NOx mass of Pollutant Emission (Tonne/hr)	0.096	0.113	0.113
LNG carrier Components			
Amount of LNG in Contract (B) m^3	**1**	**1**	**1**
Number of Years in Contract	**20**	**20**	**20**
Round Trip Distance (Nm)	**5000**	**12620**	**7420**
Number of Propellers	2	2	2
Type of Reliquefaction Plant	3	3	3
Type of Containment System	6	6	6
Vessel Speed	15	15	15
Type of Carrier and Engine	12	15	15

The only difference found between the case studies is in the size of the ship; for Case Study 1, the small conventional ship size was chosen.

As for capital cost, there is an insignificant difference in cost between low sulphur and standard fuel. However, this statement is only true if it is found that the fleet size and combination of the components are the same.

Since low sulphur fuel is more expensive than standard fuel, the operational cost is increased accordingly. In fact, the operational costs for the low sulphur fuel option were the higher of the two options tested for the same ship.

Obviously, when using low sulphur fuel the SO_x emission levels were reduced however the masses of the other pollutant emissions did not show any improvement.

5.3.1. Comparison between Routes that do and do not include the SECA Areas

It is useful to compare the results of the three tests, which are with the standard fuel condition, the standard fuel with a scrubber installed, and the low sulphur fuel condition. Table 5-8 illustrates the relative merits of each.

Case study 2, that is Qatar to Rotterdam, was selected because the combination of components among them was similar, except for the type of reliquefaction plant that was indicated for the low sulphur fuel condition result.

The fleet size for the ‘standard fuel’ and ‘standard fuel with scrubber’ conditions were the same however an additional day was allowed in order to change over the fuel in the case of the ‘low sulphur fuel’ condition, and therefore there was a small increase in the required fleet size.

The ‘standard’ and ‘low sulphur fuel’ investigations indicate similar values for capital costs because there are no additional items of equipment that need to be bought and installed onboard the ship, such as occurs in the case with ‘standard fuel with scrubber’. The difference in values between ‘standard’ and ‘low’ sulphur fuel is attributable to the difference in reliquefaction plants used.

The operational costs show small but different values for all scenarios. This is because in the case of 'standard fuel with scrubber', 10,000.00 USD was added into the annual operational costs to allow for the maintenance and power requirements for the scrubber. The price of the low sulphur fuel is higher than that of the standard fuel (as of 10th of April 2010 their costs were 477.00 and 459.00 USD/MT, respectively (BunkerWorld, 2010)).The operational costs for the 'low sulphur fuel' option will be highest if it is multiplied by the fleet size (standard fuel is USD 279.64 million, standard fuel & scrubber is USD 279.89 million, and low sulphur fuel is USD **286.39 million**).

The obvious difference in the overall mass of the pollutant emission products is in the reduction of SO_x produced in the 'low sulphur fuel' arrangement as highlighted in blue. The rest of the emission products do not show any difference in their composition.

Table 5-8: Comparison between Outside and Inside SECA Areas – identical route distance

Outputs/Inputs	**Outside SECA area rules**	**Inside SECA area rules**	
	Standard Fuel	**Standard Fuel & Scrubber**	**Low Sulphur Fuel**
Results			
No. of Ships	24.53	24.53	25.21
	The following values based on a single ship		
Capital Cost (m) USD	22.45	22.95	22.45
Operational Cost (m) USD/year	11.400	11.41	11.360
CO_2 mass of Pollutant Emission (Tonne/hr)	9.005	9.005	9.005
SO_x mass of Pollutant Emission (Tonne/hr)	0.225	0.225	0.056
NO_x mass of Pollutant Emission (Tonne/hr)	0.113	0.113	0.113
LNG carrier Components			
Amount of LNG in Contract (B) m^3	**1**	**1**	**1**
Number of Years in Contract	**20**	**20**	**20**
Round Trip Distance (Nm)	**12620**	**12620**	**12620**
Number of Propellers	2	2	2
Type of Reliquefaction Plant	4	4	3
Type of Containment System	6	6	6
Vessel Speed	15	15	15
Type of Carrier and Engine	15	15	15

One interesting difference shown in Table 5-8 is that, using a scrubber in order to reduce the level of SOx emissions is more economical than simply by using low sulphur fuel after a year of operation. This is because of the scrubber cost which is estimated to be around USD 0.5 million for a vessel, while a year of operation difference between the 'low sulphur fuel' and the 'standard fuel with scrubber' cases is USD 6.5 million, which is enough to cover the capital cost of the scrubber.

5.3.2. Comparison between Different Priorities given to the Objectives

All of the previous results have been based on the same priority level being given to each of the set objectives and since the decision making technique that has been created has the ability to select a specific priority for each of the objectives given, it is possible to see typical results from the use of this facility. Table 5-9 illustrates results from this comparison.

Table 5-9: Comparison between the effect of different priorities being given

Outputs/Inputs	**Standard Fuel**				
Base on Case Study 1	**Same weight for all**	**Higher weight for Capital Cost Only**	**Higher weight for Operational Cost Only**	**Higher weight for CO_2 Only**	**Higher weight for Capital and Operational Costs**
Results					
No. of Ships	12.1	17.7	16.2	16.2	16.2
	The following values based on a single ship				
Capital Cost (m) USD	19.64	16.76	18.96	18.96	18.96
Operational Cost (m) USD/year	9.233	9.724	8.467	8.467	8.467
CO_2 mass of Pollutant Emission (Tonne/hr)	7.749	7.895	6.982	6.982	6.982
SO_x mass of Pollutant Emission (Tonne/hr)	0.194	0.197	0.174	0.174	0.174
NO_x mass of Pollutant Emission (Tonne/hr)	0.097	0.099	0.087	0.087	0.087
LNG carrier Components					
Amount of LNG in Contract (B) m^3	**1**	**1**	**1**	**1**	**1**
Number of Years in Contract	**20**	**20**	**20**	**20**	**20**
Round Trip Distance (Nm)	**5000**	**5000**	**5000**	**5000**	**5000**
Number of Propellers	2	2	2	2	2
Type of Reliquefaction Plant	4	4	4	4	4
Type of Containment System	6	6	6	6	6
Vessel Speed	15	15	15	15	15
Type of Carrier and Engine	12	10	9	9	9

The main aim for this comparison was to ascertain whether this aspect of the decision making technique recognised and responded to any changes in relative priority or not. Regardless of which case study and scenario options are selected, the results were found to be proportionally similar. Thus, Case Study one using standard fuel was chosen for this illustration.

The required size of the fleet show significant differences as the priority changed and the minimum number of ships was actually obtained for the ‘equal priority’ case. This is because the decision making technique would compromise all objectives in order to achieve the specific conclusion. In addition, when extra priority was given to a particular objective, the compromising calculation, as mentioned in Equation 5-1, was recalculated and a new solution produced. It is not surprising therefore that the number of vessels was observed to vary with different priorities, for given similar conditions.

As far as the capital cost condition is concerned, on being given a higher priority, as expected this results in a reduction in individual vessel capital cost as compared to the other cases having different priorities. However, as a consequence, the outputs of the other objectives such as the number of carriers, operational costs, and mass of CO_2, SO_x and NO_x emissions are all increased. The reduction in the capital cost was due to the difference in the size of the vessel and type of main engine selected i.e. a reduction in size of vessel.

Similar conditions applied when the operational costs were selected to have higher priority resulting in a significant reduction in its output and the other objectives were observed to vary accordingly. Selection of the size of the carrier was again the dominant factor for this reduction. As the size reduced, the other components of the LNG carrier will require less power as explained in Chapter Three.

The production of CO_2 mass pollutant emissions is highly dependent on the thermal efficiency of the engine and the type of fuel, which link it to the operational cost. As higher priority is given to this objective, this naturally results in a reduction in the mass of CO_2 produced. Since this objective is bound to the operational cost, the combination of LNG carrier components will be similar and thus the results between them will be similar, as shown in Table 5-9.

Again, in the case of giving increased priority to both capital and operational costs, the different results that are shown compare with the equal priority assumptions. Since the main contribution to the overall cost of an LNG carrier are the size of vessel and type of engine selected, the program will choose a vessel of a size smaller than the ‘small conventional type’ and a better thermal efficiency engine than the low speed engine if available.

In all, it is clear that the decision making technique proposed in this study does respond to the assignment of relative priority levels being given to the specific objectives that are selected. This is clearly an additional advantage of the technique.

5.4. Chapter Summary

This chapter demonstrated the application of the decision making process in order to achieve the optimal combination of the main components of an LNG carrier based on the stated aim of this study. This has been achieved by developing a new simulation programme in combination with a trained ANN model.

The decision making techniques start by identifying the exact inputs and outputs of each region of the simulation. The next process was to select initial values, or types of components, and their possible increments and number of iterations before running the simulation. The weight, the relative significance of components, indicates the user specified priority to be given to particular objectives.

There are two sets of results produced by the decision making technique namely; (1) the values of each objective given, and (2) the selected components that produce those values. Since weighting values have been added in multi-objective decision making, the results produced were the same for all the objectives given.

Three case studies with different route scenarios for identical cargo delivery schedules have been considered in order to investigate the application of the multi-objective decision making techniques for LNG routes. These scenarios refer to one case outside SECA and two options for inside SECA. In addition, the ability to respond to changes in the given assigned priorities among set objectives has shown to give added value to the technique proposed in this study.

All of the results that are produced from the decision making process compared well with theoretical formulations which are shown in the appendices. Slight changes in the input variables, such as a different route distance in a case study, produced a different set of results and this is indicative of the robustness of the developed technique. Moreover, there are no contradictory results, thus illustrating the dependability of the technique. In addition, it is important to note that the technique proposed in this study considers the holistic LNG carrier as a ‘system of systems’, which, to the knowledge of the author, has not been previously considered.

6. Conclusions and Recommendations

In traditional methods for a new ship design, there would typically be an incremental change in one or more technology elements from a base design and over time this may result in a less than optimum design. The main aim of this thesis was to develop a methodology to select the optimal combination of LNG carrier components in order to minimise the fleet size, the construction and operational costs, and the total mass of pollutant emission products at the preliminary design stage. This has been achieved by proposing a procedure in which analytical tools are selected and utilised. This offers a comprehensive tool to aid in the selection of LNG carrier components so that decisions to find the optimal combination could take advantage of the tool integration.

The holistic-analytical approach consisted of a comprehensive system simulation of an LNG carrier, an artificial neural network (ANN) and an integrated ANN based multi-objective decision making simulation.

In order to achieve the above aim, the following objectives were identified and undertaken:

1. Development of an accurate mathematical model for each component in order to create an LNG carrier simulation.
2. Development of tools that could duplicate and assemble the large simulation output data efficiently and accurately with a minimum computational time
3. Application of the developed tool as a decision making technique to obtain the minimum component response and in combination, obtain the optimal operating response given the holistic integration of the individual components.

The framework of this thesis is based on maximising the profit of using LNG carriers by minimising the capital and operational costs and at the same time obeys all the rules and regulations given by international and local authorities. Minimising the costs does not imply the purchase and installation of cheap components, but requires knowledgeable consideration for future operational costs. The aim was to make a compromise between these two costs.

Six main LNG carrier components were considered, (1) the containments system, (2) the hull geometry, (3) the reliquefaction plant system, (4) the power prediction variables, (5) the main propulsion systems, and (6) the mission profile variables. In order to build an appropriate simulation model for an LNG carrier, each of these components needed to be translated into an appropriate mathematical model.

The main challenge in creating the mathematical model for each component was developing an understanding of the behaviour and limitations. At the same time, the accuracy of results was dependent on selecting or creating the appropriate formulation. The simulation had eight high impact input variables that were identified, namely: (1) The type of carrier class and propulsion engine, (2) the amount of LNG to be transported as stated in the contract, (3) the number of years set in the contract, (4) the round trip distance between the export and import ports, (5) the carrier speed, (6) the type of containment system to be selected, (7) the type of reliquefaction plant chosen, and (8) the type of hull geometry. While the outputs were fleet size, capital and operational costs, and the mass of CO_2, SO_x and NO_x emission products.

The simulation was conducted based on the above parameters and produced a total possible combination of 311,040 outputs. An ANN model was built and trained using the simulation input-output data. Accurate results were obtained from the ANN model, where the mean square errors (MSE) were close to zero, and the regression values were almost one. Investigations were performed to identify the consequences of changing each input variable. The results were presented in graphical format and found to be in reasonable agreement with related theories and practical experimental solutions carried out by other researchers. The trend of the results reconfirmed the accuracy of the mathematical models that were created previously.

Even though the simulation method and ANN were proven to be effective in producing output data, these techniques were unable to produce an optimum solution. Thus, an additional decision making technique was required in order to achieve the aim of this thesis. The proposed technique was an integrated decision making tool; an ANN model and a simulation programme, both of which have been described in detail, applied and validated in this thesis. The ANN/ simulation combination has been demonstrated to work successfully with the results agreeing with the related theories. This shows the reliability of this decision making technique. Additional investigations in line with current problems associated with LNG carriers such as operation in the Sulphur Emission Control Area (SECA) and CO_2 emission levels were also performed. From the results, using 'standard fuel with scrubber' was found to be more economical in the long term for LNG operation compared to the use of 'low sulphur fuel'. Moreover, this decision making technique has the additional option of selecting the priority assigned to the objectives. Investigation of this was also performed and discussed.

The contribution of this research is to provide an holistic decision making tool for LNG carriers which has not previously been available. The current published data associated with LNG vessels only focuses on an individual system, thus it does not indicate the whole picture of the LNG carrier. In this research all of the systems have been integrated in one platform so the interaction between them could be considered

This research has contributed in several ways. Generally, it provides realistic scenario analysis of LNG carriers. All rules and regulations have been adopted; thus, it provides a holistic view of LNG carriers.

This research also contributes to knowledge in decision making processes for identifying optimum combinations of LNG carrier components. This process has been successfully demonstrated by linking the components together in a single platform. The previous studies have only focused on selected components while this research has illustrated the overall relationship between the components. Thus, this methodology is applicable for similar engineering issues especially when dealing with a conflict of interest in complex systems.

A software tool has been developed that provides comprehensive results for industrial scenarios and which could be used as a preliminary design tool to aid in the optimisation of new build LNG carriers.

6.1. Recommendations for future work

This thesis discussed LNG carrier systems and the potential ways to achieve given aims for new constructions in the future. The investigations, examinations and simulation analysis have been carried out in order to achieve these aims by developing a general methodology that can be applied not only to LNG carriers but to all types of ship and engineering decision making problems.

The main consideration in developing and validating a robust methodology for ship decision making techniques has been achieved and is evidenced in the reasonable comparison of the results obtained from the proposed technique with theoretical solutions and experimental results of related studies. Given time and funding constraints however, it has not been possible to investigate each of the related areas in as much detail as was originally desired. Thus, there are still many areas which are deserving of further attention.

Concerning the LNG carrier component simulation model, several parameters such as ambient temperature, price of the materials and fuels, overhead, manpower and specialist costs have been given constant values. Power prediction variables which depend on factors such as size and type of the ship, and compositions of the fuel for mass of emission product calculations were similarly assumed constant. Their actual values should however be used to generate more accurate results.

The level of detail of the LNG carrier component simulation should be improved depending on the purpose for which the model is being developed. Some areas such as thermodynamic heat transfer and surface tank area calculations which involve many considerations should be further investigated in order to have a more comprehensive simulation model. In addition, the calculations of fleet size in this study have been based on calm sea conditions and the uninterrupted sailing of the ship without unscheduled stops. However, the calculation of fleet size should incorporate a model which considers additional time resulting from unexpected and unavoidable delays.

Considering the ANN modelling, use of a wider range of input data in training the model would improve the accuracy of predicted results. Further experiments with the ANN structure and its transfer functions could also be undertaken to ensure accuracy of the results.

Performance of an integrated ANN based multi-objective decision making technique can also be improved by further investigation of various parameters. This thesis has been mainly concerned with developing a general methodology for solving complex systems with a conflict of interests rather than fine-tuning of parameters.

Finally, instead of acting as a verification tool toward a new construction of LNG carrier, this proposed technique, if supported by a suitable simulation model could be used as both a design and operational tool for application in the ship industry, and a potential extension to line-production manufacturing processes.

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Appendix 1

Mathematical Modelling of Containment System

The containment system consists of a primary and a secondary barrier and a set of insulation materials in between the barriers and the tank wall. In addition to providing a tank to hold the liquid cargo, the main function of the containment system is to limit the penetration of external heat into the cargo hold by using low thermal insulation material which can reduce the generation of boil off gas (BOG). The presence of BOG in the cargo tank will increase the tank pressure and if unvented will eventually damage the membrane of the containment system because it is very sensitive to pressure (ABS, 2003).

External Ambient Heat Influx to LNG Tank

Ambient and seawater temperatures vary according to geographic location, time of day, weather conditions, and season. These temperatures are clearly considerably higher than those within the LNG itself (-160^{o}C). According to the Second Law of thermodynamics, heat flows from higher to lower temperature regions (Holman, 2010; Cengel, 1997). Thus, the heat penetration from the outside into the cargo hold is hard to avoid due to the very large temperature differences between them, which is typically approximately 180^{o}C. The calculation of heat transfer comes from Fourier's law (Joel, 1996), which states that the heat transfer is a combined function of thermal potential difference and total thermal resistance. The Fourier equation can be written as:

$$\dot{q} = \frac{\Delta T}{\Sigma R_t}$$

Where:

$\dot{q}$ is heat transfer flow rate

ΔT is thermal potential difference

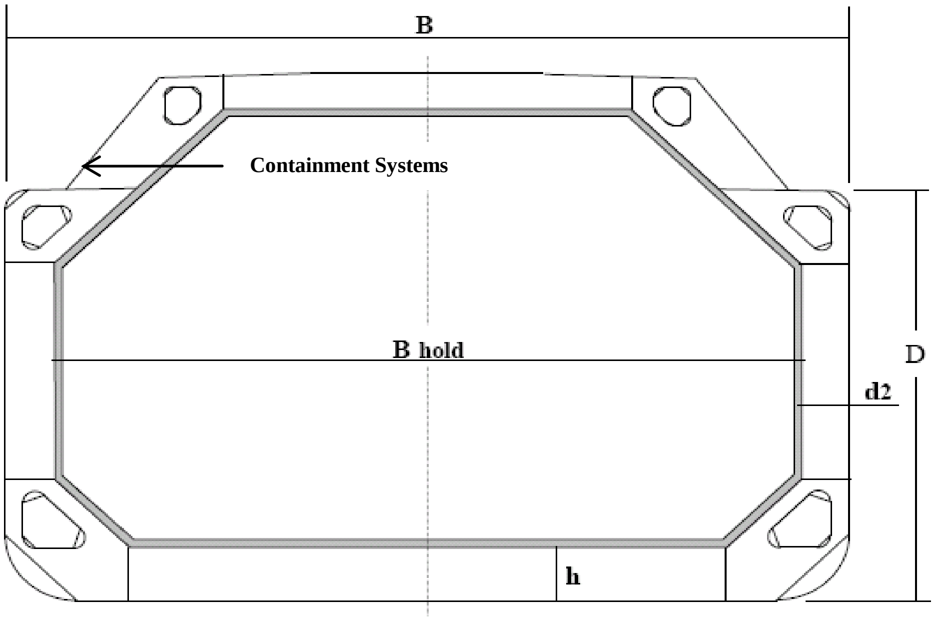
$\sum R_t$ is the various thermal resistances of the element layers (K/W)

It is clear that the heat flow rate can only be reduced by either reducing the thermal potential difference or by an increase in total thermal resistance, which is a function of thermal conductivity, thickness of materials and area of resistance to flow, or by a combination of the two. Since the thermal potential difference in an LNG application is large, the only option is to increase the total thermal resistance of the containment system. This can be done by increasing the thickness of the insulation material and/or by using a series of materials having low thermal conductivity coefficients. However, both of these options have an impact on the other components of the LNG carrier, such as an increase in overall costs. For example, a low thermal conductivity material might be more expensive, reduce the amount of cargo carried because an increase in thickness will reduce the cargo volume or there might be an increase in the weight of the vessel for the same volume of cargo which eventually increases the ship resistance and requires more power to manoeuvre the ship according to its mission profile. A compromise between the various components is thus necessary in order to handle this problem efficiently.

There are two basic types of LNG containment systems based on the geometric shape of the tank: prismatic (wall type) or spherical.

Modelling of Prismatic Tank Containment Systems

There are only two types of prismatic cargo containment systems currently in use, the membrane type with a fully effective secondary barrier (No. 96, MARK III and CS1) and the **S**elf-supporting **P**rismatic shape IMO Type **B** (SPB) tank with a partial secondary barrier. A typical cross section of a prismatic tank is illustrated in Figure 1-1



B is breadth, D is depth, L is length, h is height and d is draft

Source: GTT Photo library

Figure 1-1: Typical Cross Section of Prismatic Tank

The mathematical techniques that are required to calculate the heat transfer rate for a complete prismatic containment system are complex and some assumptions have to be made in order to simplify the problem. The assumptions include:

- The calculation is performed in steady state conditions with a stabilised temperature gradient across the system.
- Only conduction heat transfer has been considered (i.e. no radiation effects).
- The same outside temperature exists around the tank and its insulation system. The assumption of uniform outside temperatures (i.e. no differences between air and water temperatures) suggests the hull equilibrates the temperature.
- The total area of the tanks is based on the number of the tanks multiplied by midship tank area in square metres (i.e. no difference in the size of the tanks on a given vessel).

The following sections illustrate the typical arrangement of each prismatic containment system including the thicknesses and materials used and provide a formulation of the total thermal resistance per unit area.

- **Modelling of No 96 Tank Containment Systems**

The cross section of the wall of a No 96 tank is shown in Figure 1-2. Nitrogen gas is supplied in between the resin beads and the vessel's inner hull for the purposes of cargo leak detection. Resin beads, also known as mastic, are used to bond the containment system to the ship's double hull, having two purposes: (1) to compensate for the surface irregularities of the inner hull and to transmit the mechanical cargo-induced loads to the hull, and (2) as a load bearing filler for corner panels and retainers (TNA, 2008).

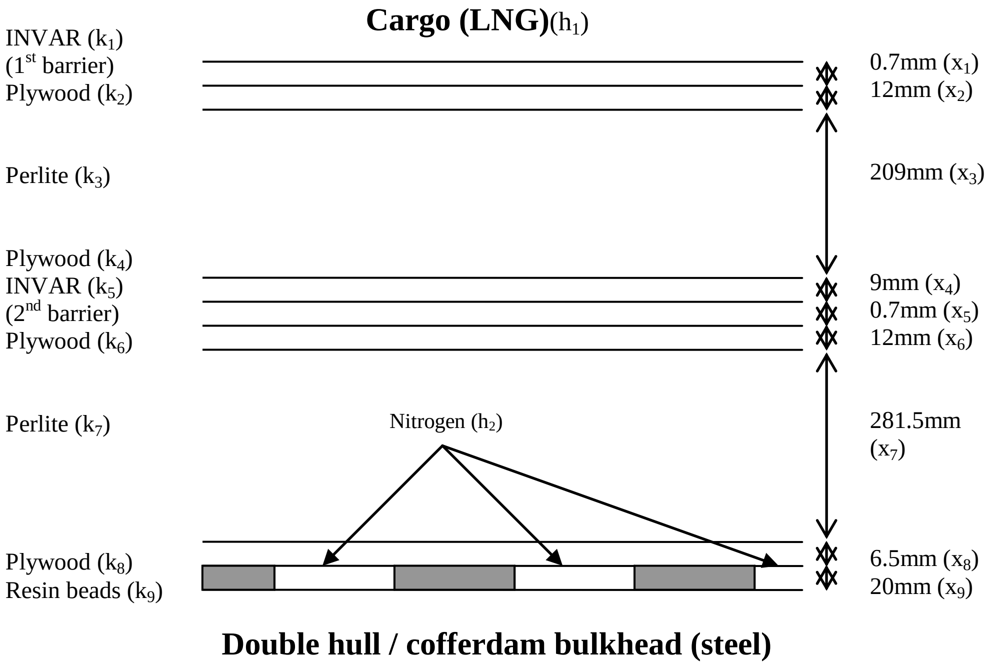


Figure 1-2: Typical Cross Section of No 96 Containment Systems

The total thermal resistance per unit area for a No 96 Containment System is given by: $\Sigma R_{No\ 96}$ =

$$\frac{1}{h_1}+\frac{\Delta x_1}{k_1}+\frac{\Delta x_2}{k_2}+\frac{\Delta x_3}{k_3}+\frac{\Delta x_4}{k_4}+\frac{\Delta x_5}{k_5}+\frac{\Delta x_6}{k_6}+\frac{\Delta x_7}{k_7}+\frac{\Delta x_8}{k_8}+\frac{\left(\frac{1}{h_2}\right)\left(\frac{\Delta x_9}{k_9}\right)}{\left(\frac{1}{h_2}\right)+\left(\frac{\Delta x_9}{k_9}\right)}$$

- **Modelling of MARK III Tank Containment Systems**

The cross section of the wall of a MARK III tank is shown in Figure 1-3. Nitrogen gas is supplied in between the mastic and the vessel's inner hull for leak detection and also within the corrugated primary barrier. The obvious differences between the MARK III and No 96 systems are in the primary and secondary barriers and the insulation materials. Also, the thickness of the containment system is reduced by about 50 percent for the MARK III compared with the No 96 system.

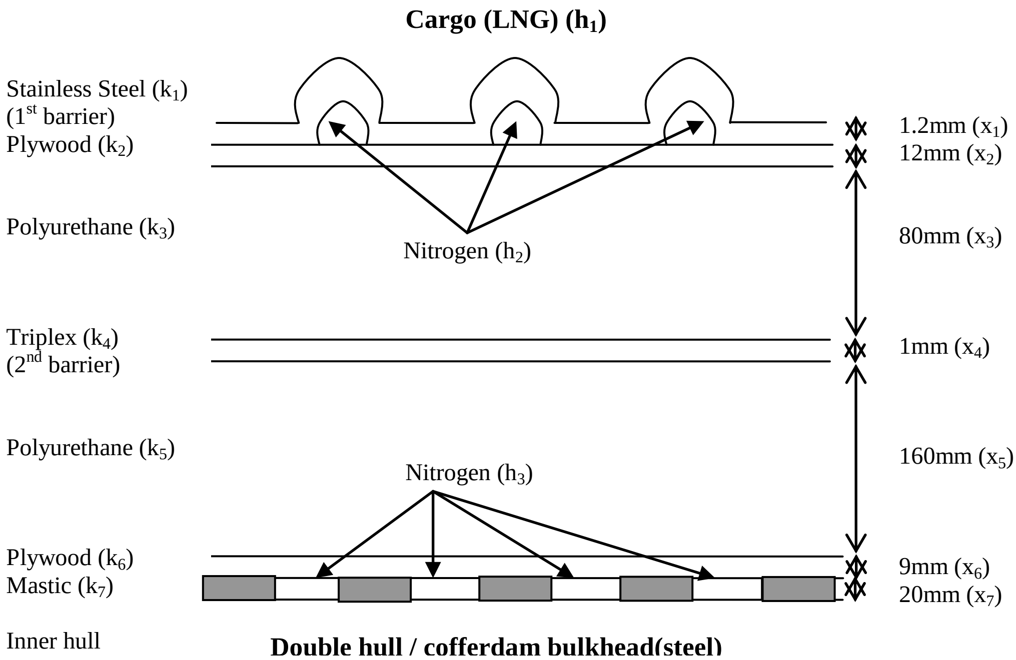


Figure 1-3: Typical Cross Section of MARK III Containment System

The Total Thermal Resistance per unit area for the MARK III Containment System is given by:

$$\Sigma R_{\text{MARK III}} = \frac{1}{h_1} + \frac{\left(\frac{\Delta x_1}{k_1}\right)\left(\frac{1}{h_2}\right)}{\left(\frac{\Delta x_1}{k_1}\right)+\left(\frac{1}{h_2}\right)} + \frac{\Delta x_2}{k_2} + \frac{\Delta x_3}{k_3} + \frac{\Delta x_4}{k_4} + \frac{\Delta x_5}{k_5} + \frac{\Delta x_6}{k_6} + \frac{\left(\frac{\Delta x_7}{k_7}\right)\left(\frac{1}{h_3}\right)}{\left(\frac{\Delta x_7}{k_7}\right)+\left(\frac{1}{h_3}\right)}$$

- **Modelling of Combined System Number 1 (CS1) Containment Systems**

The cross section of the wall of a CS1 tank is shown in Figure 1-4. Nitrogen gas is supplied in between the mastic and inner ship's hull for leak detection. The primary barrier is similar to that of the No 96 containment system; however, the secondary barrier and the insulation materials are the same as in the MARK III system. Since the thickness of the containment system is highly dependent on the type of insulation material, the CS1 system will have almost the same thickness as the MARK III system.

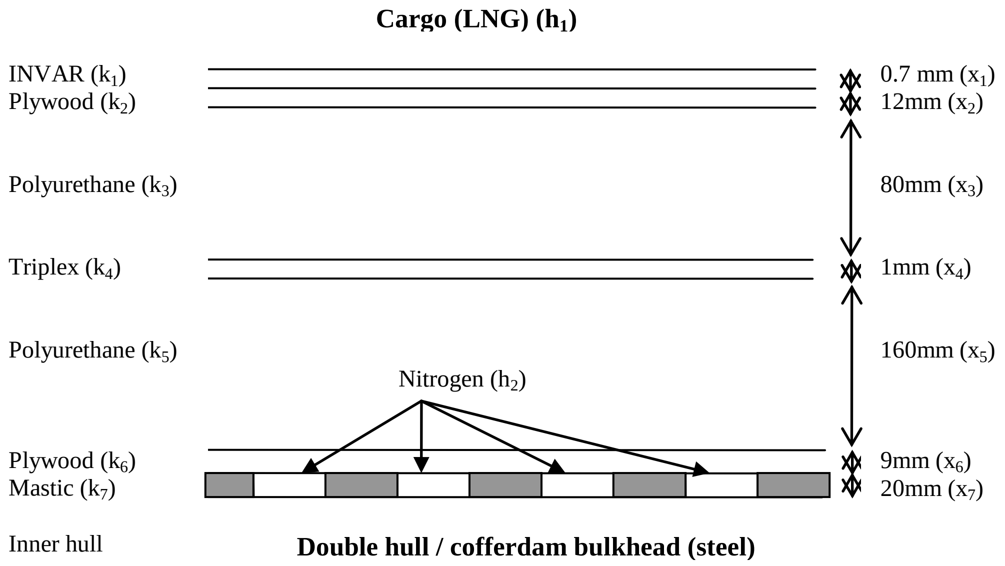


Figure 1-4: Typical Cross Section of CS1 Containment System

The Total Thermal Resistance per unit area for the CS1 Containment System is given by:

$$\Sigma R_{CS1} = \frac{1}{h_1} + \frac{\Delta x_1}{k_1} + \frac{\Delta x_2}{k_2} + \frac{\Delta x_3}{k_3} + \frac{\Delta x_4}{k_4} + \frac{\Delta x_5}{k_5} + \frac{\Delta x_6}{k_6} + \frac{\left(\frac{\Delta x_7}{k_7}\right)\left(\frac{1}{h_2}\right)}{\left(\frac{\Delta x_7}{k_7}\right) + \left(\frac{1}{h_2}\right)}$$

- **Modelling of Self-supporting Prismatic shape IMO Type B (SPB) Tank Containment Systems**

The SPB containment system consists of a structurally complete freestanding, self-supporting independent prismatic tank. The cargo tank rests on the hull structure within the hold space and is supported and restrained by the hull structure in a manner that prevents forces on and movement of the tank caused, due to ship wave induced motions and hull deflections. The tank structure itself is designed to be able to resist the cargo pressure forces and the effects of the accelerations that are a result of ship motions in waves. The cross section of a CS1 tank wall is shown in Figure 1-5. SPB tanks only need a partial secondary barrier (IGC, 1993). The three dimensional shape of the tank is similar to that of a membrane tank.

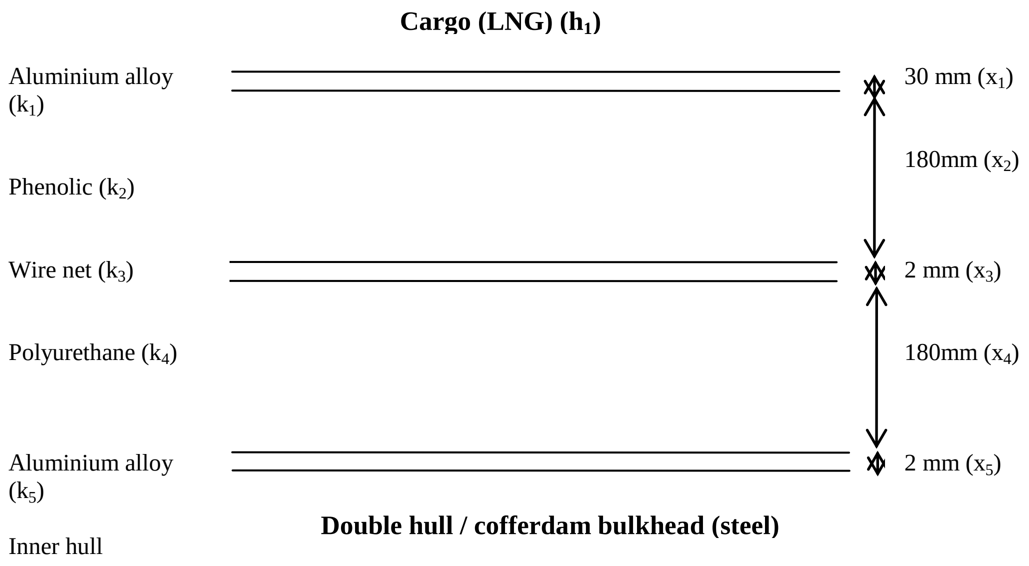


Figure 1-5: Typical Cross Section of SPB Containment System

The total thermal resistance per unit area for the SPB Containment System is given by:

$$\Sigma R_{SPB} = \frac{1}{h_1} + \frac{\Delta x_1}{k_1} + \frac{\Delta x_2}{k_2} + \frac{\Delta x_3}{k_3} + \frac{\Delta x_4}{k_4} + \frac{\Delta x_5}{k_5}$$

Modelling of Spherical Tank Containment Systems

The first design of Type B independent tanks is the Moss-Rosenberg arrangement. It was licensed by Kvaerner and is also known as the Kvaerner-Moss system. The first generation of this configuration of LNG carriers were the vessels named *Norman Lady* and *AsakeMaru*. The tanks were made from 9 % nickel steel, having a 36.6 m diameter and with the ships having five spherical tanks with a combined 125,000 m^3 capacity. However, nowadays the containment system is made from aluminium alloy (ABS, 2003).

The cargo containment system is made of an unstiffened spherical shell tank supported at the equator by a vertical cylindrical skirt. The bottom of the cylindrical skirt is welded to the ship hull double bottom structure. The skirt supporting the tank thus transmits all of the loads from the tank to the hull. These loads are tank and LNG cargo self-weight and include the effects of ship motion-induced accelerations. A stainless steel thermal 'break' has been introduced in order to reduce the heat gain in the skirt (Yuasa et al., 2001). The cross section of a Spherical Containment System is shown in Figure 1-6.

The Total Thermal Resistance per unit area for the Spherical Containment System is given by:

$$\Sigma R_{Spherical} = \frac{1}{h_2 A_o} + \frac{r_6 - r_5}{4\pi k_5 r_6 r_5} + \frac{r_5 - r_4}{4\pi k_4 r_5 r_4} + \frac{r_4 - r_3}{4\pi k_3 r_4 r_3} + \frac{r_3 - r_2}{4\pi k_2 r_3 r_2} + \frac{r_2 - r_1}{4\pi k_1 r_2 r_1} + \frac{1}{h_1 A_i}$$

Where:

A_o is outer surface area of the tank structural shell (m^2)

A_i is inner surface area of the tank structural shell (m^2)

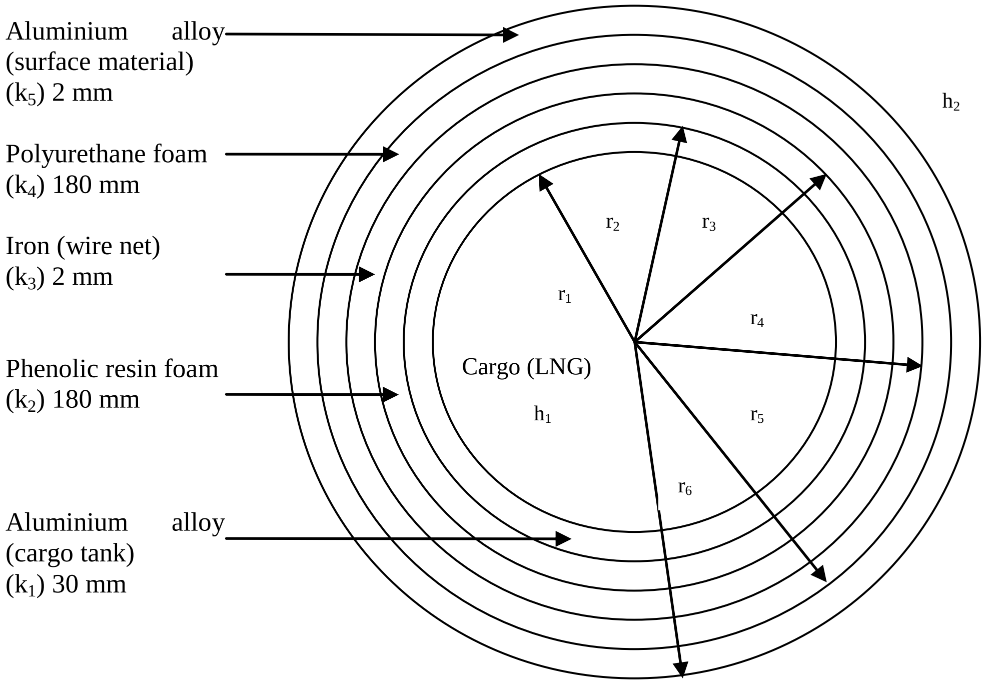


Figure 1-6: Typical Cross Section of Moss Insulation Tank

A summary of the materials and the typical thicknesses of some existing containment systems are given in Table 1-1.

Table 1-1: Summary of Materials used in some Containment System

Elements	**Containment Systems**				
	No 96	**MARK III**	**CS1**	**SPB**	**MOSS**
Primary Barrier	INVAR 36% Nickel	Corrugation Stainless Steel Membrane	INVAR 36% Nickel	Aluminium Alloy or Stainless steel	Aluminium Alloy
Secondary Barrier	INVAR 36% Nickel	Triplex	Triplex	-	-
Major Insulation Material	Perlite	Polyurethane Foam (PUF)	Polyurethane Foam (PUF)	Phenolic & Polyurethane	Phenolic & Polyurethane
Overall Thickness (mm)	551.4	283.2	282.7	394	394

It can be seen from Table 1-1 that the main difference between the containment systems, other than the materials selection, is in the overall thickness. With a thicker containment system, the amount of the cargo will be reduced for a fixed vessel size and at the same time this will require additional power due to the extra weight. One way to reduce the overall thickness is by changing the insulation materials, and/or by adjusting the thickness of the system to achieve a desire value of total thermal resistance. This can be done by implementing the heat transfer formula in a simulation model of the containment system and then by examining the effects of varying the input parameters.

The system was modelled in LabVIEW and the inputs and outputs of the model are shown in Figure 1-7. The input parameters can be varied in order to observe the output patterns. At the same time, the outputs were linked to other systems such as the 'cost of containments system' that was connected to life cycle cost analysis, and the 'total heat transfer' model used to calculate the amount of BOG produced.

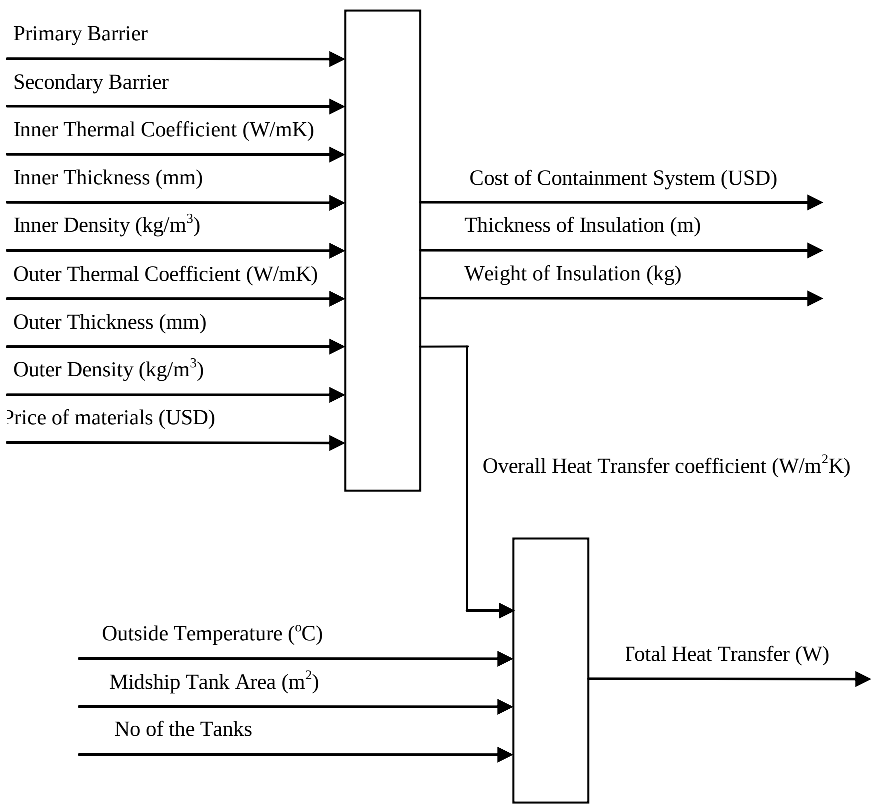


Figure 1-7: The Inputs and Outputs of the Containment System Model

Figure 1-7 it can be seen that one of the elements required in order to be able to calculate the total heat transfer is area. Calculation of the areas for containment systems is quite straightforward; it is a function of the number of tanks, breadth, capacity and the geometric shape of the tank, as shown in Figure 1-8.

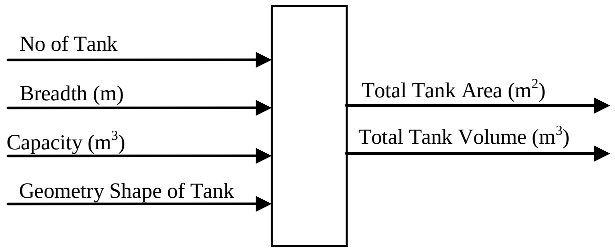


Figure 1-8: The Inputs and Outputs of the Containment System Area

There are two shapes of tank in current usage: spherical tanks with the surface area formula given by $4\pi r^2$ where *r* is the radius of the tank, and prismatic tanks with an octagonal transverse shape with the surface area determined using the following formula:

$$
\begin{aligned}
Area &= 2\{[(D - X\sin 45^o - Y\sin 45^o)\cdot B + L] + X\cdot[(B - 2X\cos 45^o) + (L - X\sin 45^o)] \\
&+ Y\cdot[(B - 2Y\cos 45^o) + (L - Y\sin 45^o)]\} + [(B - 2X\cos 45^o)(L - 2X\cos 45^o)] \\
&+ [(B - 2Y\cos 45^o)(L - 2Y\cos 45^o)]
\end{aligned}
$$

Where B is breadth in metres, D is depth in metres, L is length in metres, X is slope X in metres, and Y is slope Y in metres, as illustrated in Figure 1-9.

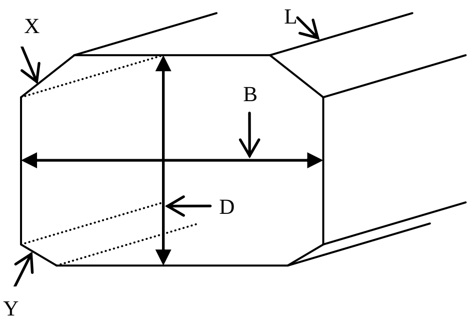


Figure 1-9: Shape of the Prismatic Tank

Appendix 2

Mathematical Modelling of a Reliquefaction Plant

A reliquefaction plant is a system that is used to convert BOG back into liquefied natural gas, eventually returning it back to the cargo tanks after the gas flows through a series of heat exchangers. This system can be divided into two main cycles, the BOG and the nitrogen gas cycles (Pil et al., 2006). The BOG cycle consists of four main elements: the pre-cooler, the Low Duty (LD) compressors and pump, the heat exchangers and the expansion device, as illustrated in Figure 2-1. The pre-cooler acts as a filter to ensure that only dried BOG can flow into the LD compressor. The compressors and the pump firstly increase the pressure of the BOG and then reliquefy it, while the heat exchangers are where the BOG phase changes happen. The 'expansion device' is used to reduce the reliquefied BOG pressure to close to the cargo tank operating pressure by a throttling effect before returning the reliquefied BOG to the cargo tank.

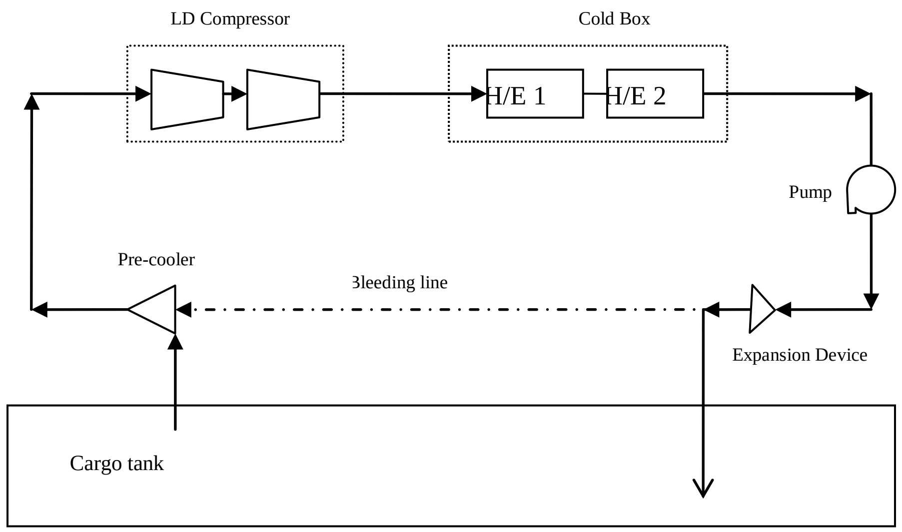


Figure 2-1: Typical Cycle of the Boil-Off Gas (BOG) Reliquefaction Process

The nitrogen (N_2) cycle also consists of four main elements; the coolers, the High Duty (HD) compressors, the heat exchangers and the expander, as shown in Figure 2-2. There are three stages of compressor and then cooler actions. The coolers are used to reject the heat generated from the action of the compressor and this happens at constant pressure in each stage. A typical mass flow rate through each of the coolers is 20 kg/s and it comes from a sea water pump (Kah, 2007). The second element is the HD compressor, the main purpose of which is to develop a high nitrogen pressure before entering the expander device. In the expander device, this high pressure nitrogen will be expanded in an isentropic process, which results in a large temperature drop in the nitrogen fluid. This temperature drop is then used to condense the BOG in the heat exchangers.

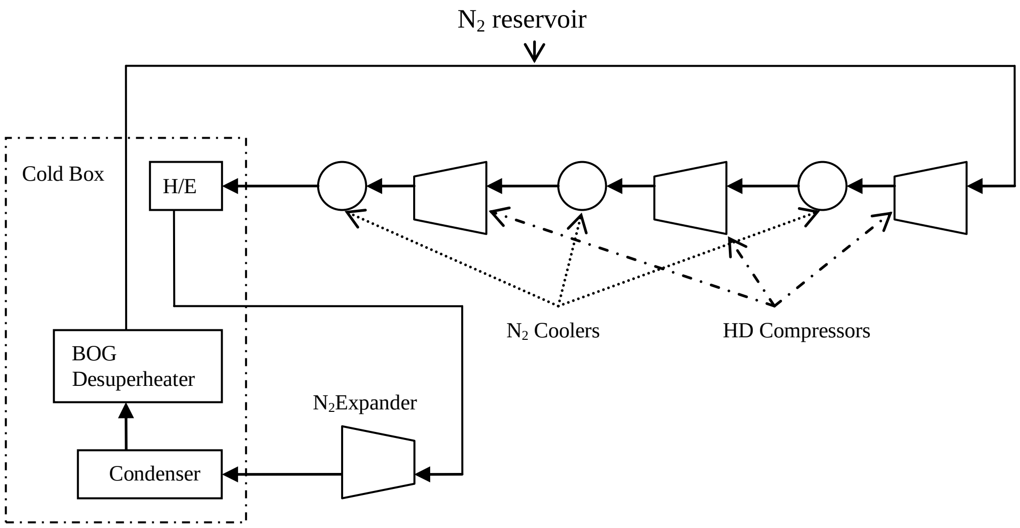


Figure 2-2: Typical Cycle of the Cryogenic Nitrogen gas Process

Currently there are two companies that manufacture reliquefaction plants: Hamworthy and Cryostar. Although they use the same thermodynamic cycle to carry out the process of reliquefy the BOG, they use different temperatures and pressures for each cycle. The values of pressures and temperatures for each cycle for Hamworthy and Cryostar equipment are illustrated in Table 2-1 and Table 2-2 respectively.

Table 2-1: Values of Pressure and Temperatures of the BOG Cycle

	Low Duty Compressor		Heat Exchanger		Separator/ Expansion	
	Hamworthy	**Cryostar**	**Hamworthy**	**Cryostar**	**Hamworthy**	**Cryostar**
Suction pressure (bar)	1.1	1.1	4.5	4.8	6.5	4.7
Suction Temperature (^{o}C)	-125	-120	-25	-80	-159	-165
Discharge pressure (bar)	4.5	4.8	4.5	4.7	2.3	3.0
Discharge temperature (^{o}C)	-25	-80	-159	-165	-165	-165

Source: (Sillars, 2007)

Table 2-2: Values of Pressure and Temperatures of the Nitrogen Cycle

	N_2 compressor		Heat Exchanger		N_2 Expander		Condenser	
	Hamworthy	**Cryostar**	**Hamworthy**	**Cryostar**	**Hamworthy**	**Cryostar**	**Hamworthy**	**Cryostar**
Suction pressure (bar)	13	9.1	53	48	53	47	13	9.5
Suction Temperature (^{o}C)	40	42	42	43	-110	-105	-163	-168
Discharge pressure (bar)	53	48	53	48	13	9.5	13	9.4
Discharge temperature (^{o}C)	100	110	-110	-130	-163	-168	-140	-140

Source: (Sillars, 2007)

The generation of BOG will be continuous throughout a journey, even with a highly efficient containment system. The amount of the BOG generated is the main input to the reliquefaction plant model as shown in Figure 2-3. There are many factors that contribute to the calculation of the amount of BOG that is generated. Among the factors are the insulation materials selected, the insulation material thicknesses, the size of the tanks, and the outside temperatures. However, the only variables that cannot be controlled are the outside temperatures (air, sea and solar/radiant).

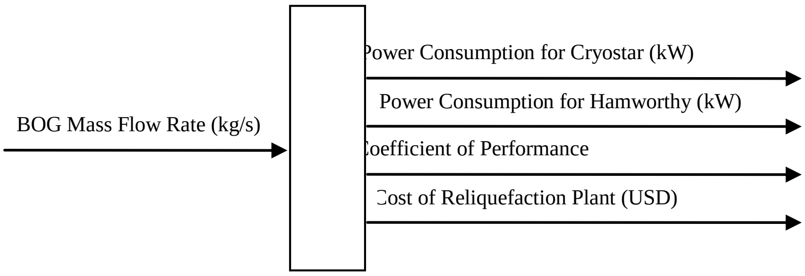


Figure 2-3: The Inputs and Outputs of the Reliquefaction Plant Model

One of the outputs of the reliquefaction plant calculations are the power consumption and thus the system's contribution to operational costs. Studies of the operational costs of reliquefaction plants have been made by many researchers such as by Pil et al (2006) and Moon et al (2007). The power consumption can be calculated by summarising all of the power required by the various items of equipment that are required to operate the reliquefaction plant. This equipment includes the low duty and high duty compressors, the reliquefaction BOG pump, the nitrogen compressors and the nitrogen expander. However, some assumptions have to be made to simplify this calculation:

- The calculation is performed assuming steady state conditions.
- The system is fully insulated from its external environment, so no heat is gained or lost from the system (adiabatic condition).

The formula to calculate the power or work done for each item of equipment in a complete reliquefaction plant is (Eastop and McConkey, 1993):

$$P = \dot{W} = \dot{m}_a (\Delta h)_b$$

Where:

P is power (kW)

$\dot{W}$ is work done (kW)

$(\Delta h)_b$ is the differential enthalpy between the inlet and the outlet of each item of equipment (kJ/kg), and

$\dot{m}_a$ is mass flow rate through each item of equipment (kg/s)

This equation is based on a perfect heat exchange process, although in reality this scenario is hardly ever achieved because there is always some energy loss incurred due to moving parts, etc (Turns, 2006). Therefore, an isentropic efficiency (η_i) figure is used. Thus, the total power consumed can be calculated as:

$$Power_{total} = \frac{\sum W_n}{\eta_i}$$

Where:

$\sum W_n$ is total work done by each of the LD and HD compressors, the reliquefaction BOG pump, the nitrogen compressors and the nitrogen expander, and where

η_i is the isentropic efficiency for the whole system.

The total power calculation may then be translated into the cost associated with meeting the average demand. These costs were added into the overall operation cost section in the Life Cycle Costs Analysis (LCCA). Since the reliquefaction plant power consumption depends on the amount of BOG produced in a given period of time and assumed environmental conditions, which are interrelated with the other components of the LNG carrier, the operational costs will thus vary accordingly. The actual power consumption of this plant can only be estimated when all the other system components have been considered and selected.

Appendix 3

Mathematical Modelling of Propulsive Power Prediction

The Power Prediction method is a tool that is employed to calculate the propulsive power requirement for a new vessel based on all the components that are related to it. There are many variables involved in this calculation, however, the main selected variables are normal sailing speed and the total resistance of a ship through a seaway as illustrated in Figure 3-1 (Nabergoj and Orsic, 2007; Holtrop and Mennen, 1982). In this thesis, this power prediction formula is based on research carried out by Holtrop and Mennen (1982), who followed the International Towing Tank Conference (ITTC) 1978 approach.

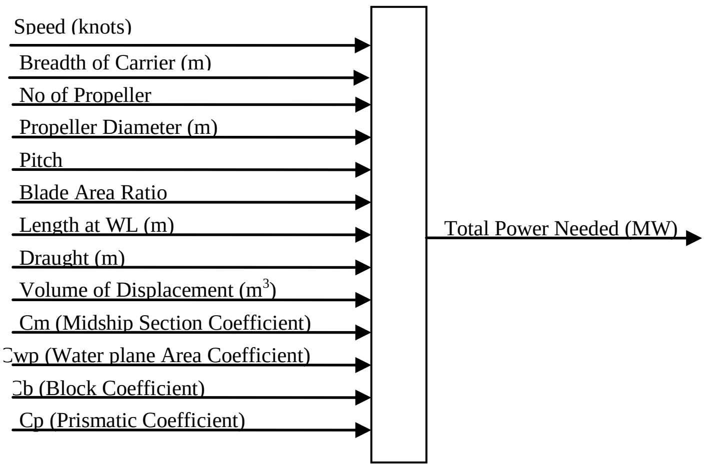


Figure 3-1: The Inputs and Outputs of the Power Prediction Model

Holtrop and Mennen proposed the following equation to calculate the total hydrodynamic resistance to the forward motion of a ship:

$$R_{total} = R_F\,(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

Where:

R_F is the frictional resistance according to the ITTC-1957 friction formula

$1+k_1$ is a form factor describing the viscous resistance of the hull form in relation to RF.

R_{APP} is the resistance of any appendages.

R_W is the wave-making and wave-breaking resistance.

R_B is the additional pressure resistance of a bulbous bow near the water surface.

R_{TR} is the additional pressure resistance of an immersed transom stern.

R_A is model-ship correlation resistance factor.

The power prediction can be obtained by multiplying the total resistance by the speed of the ship. The author developed an engine database that could be used as a look up table. Based on the power prediction result, the selection of the main propulsion machinery system can be carried out using the main engine database. However, before selection of the main propulsion can take place, all the related components in the LNG carrier must be checked for any conflict of interest between them in achieving the given objective.

Appendix 4

Mathematical Modelling of Life Cycle Costs Analysis

The Life Cycle Costs Analysis (LCCA) can be sub-divided into two main groups, namely capital costs and operational costs. The operational costs can be further sub-divided into fixed and variable costs. A summary of the inputs and outputs of each of the cost centres is illustrated in Figure 4-1.

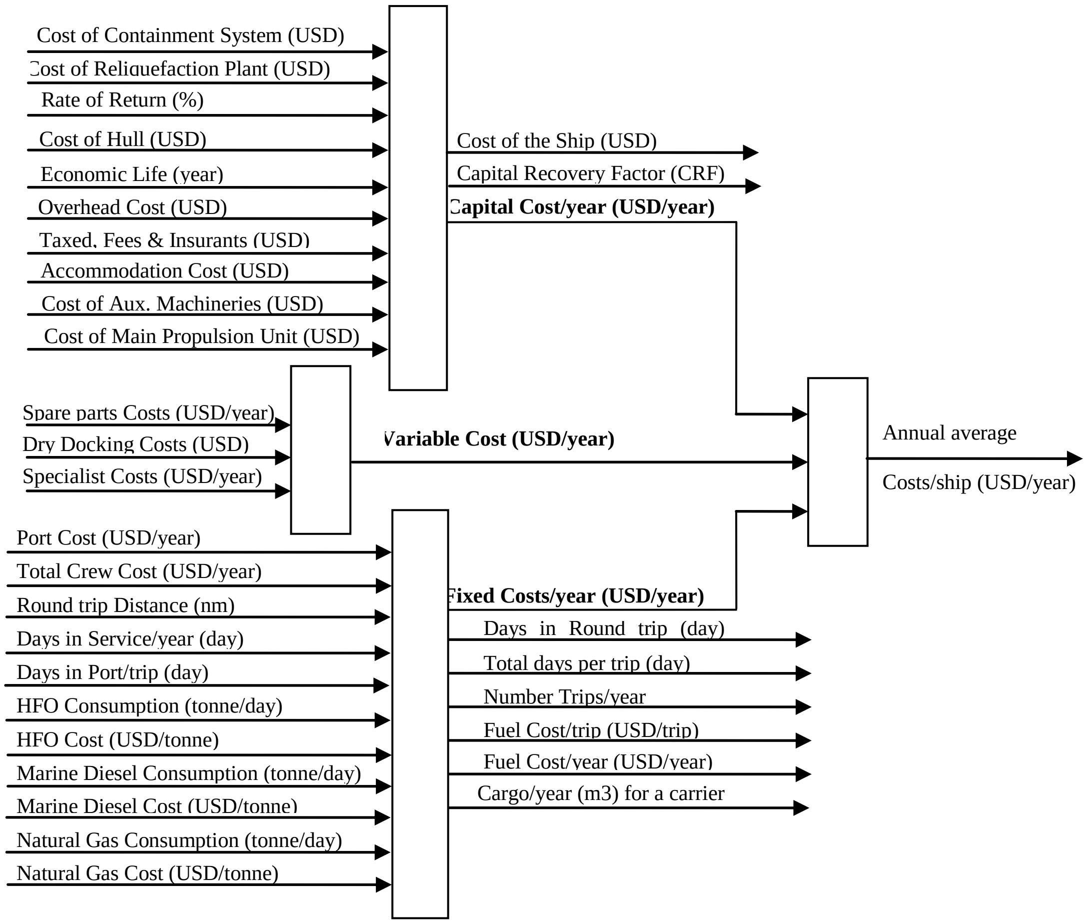


Figure 4-1: The Inputs and Output of the LCCA Model

The capital cost is a function of the initial ship costs and the Capital Recovery Factor (CRF) (Buxton, 1976). The ship cost is a summation of the costs for the hull, the outfit, the containment system, the reliquefaction plant, the propulsion and machineries, the overheads, and the taxes, fees and insurance.

The Capital Recovery Factor can be calculated as:

$$CRF = \frac{i}{1-(1+i)^{-N}}$$

Where:

N is the required economic life (year)

i is Rate of Return (%)

The Fixed cost per year is a summation of the fuel cost, the total crew costs, the port costs, and the operational costs for the reliquefaction plant. The fuel cost per year can be calculated by multiplying the fuel cost per trip by the number of round trips per year. Normal fuels used for LNG carriers are a combination of heavy fuel oil, marine diesel and natural gas boil off (BOG) and these fuel prices vary over time. Meanwhile, the variable costs per year are a summation of specialist, spare parts, and dry docking and maintenance costs. All of the components of the LNG carrier were drawn into the life cycle cost analysis section to calculate the total running costs of the ship or fleet. Since some of the costs are dynamic according to time and demand, their values were fixed in order to simplify calculations.

Drawing together all of the components into the LCCA can only be done if they all communicate using a single nomenclature or language. This can be done by defining each of the LNG carrier components in a mathematical model. Once all of the components of the LNG carrier had been transformed into compatible mathematical models, the next step was to create a simulation of the overall system behaviour for the LNG carrier.

Appendix 5

Mathematical Modelling of Pollutant Emissions

Emission products result from the combustion of fossil fuels in the propulsion machinery. A simple chemical equation to illustrate the stoichiometry combustion for fossil fuels is given as:

$$CH_4 + 2O_2 + N_2 = 2H_2O + CO_2 + N_2$$

Where:

CH_4 is methane from the BOG

O_2 and N_2 are from the air intakes

The products of combustion are mainly water, carbon dioxide and nitrogen (Cengel, 1997). Nitrogen is an inert gas; therefore it is not involved in combustion within certain limits. However, at extremely high temperatures, nitrogen can be combined with oxygen to produce nitrogen oxides (NO_x) which can cause depletion of the ozone layer and contribute to climate changes (Brown, 2007). Although CO_2 is a stable gas, it also contributes to climate change. Moreover, if incomplete combustion occurs, it will produce unburned hydrocarbon, carbon monoxide and soot, which further adds to the problem. The situation becomes even worse when Heavy Fuel Oil (HFO) or residual fuel is used as this includes a mixture of sulphur and the sulphur oxides (SO_x) that are produced from its combustion are a main contributor to acid rain (Kremser, 2007).

CO_2, SO_x and NO_x are the three major components of propulsion machinery emission gases. These emissions can be minimised with the help of new technologies, and this reduction is required by local and international rules. S_{Ox} can be reduced by using low sulphur fuel or by passing exhaust gases through a scrubber tower. However, low sulphur fuel is more expensive than the normal HFO and having the scrubber tower itself is an additional capital cost and leads to an increase in operational costs in term of both the power consumption and maintenance. Additionally, there are also a number of solutions to reduce NO_x. One of these is by injecting water into the combustion chamber. Other ways are by cooling the exhaust gas in a similar manner to a scrubber tower and by injecting catalytic compounds into the exhaust gases. All of these additional items of equipment will again increase the capital and operational costs for the carriers. In the case of CO_2, the only way to reduce it is by minimising the actual fuel combustion (MER, 2009; Brown, 2007; Kremser, 2007). This can be done by reducing the speed and/or by reducing the size of the carrier. However, these reductions are not necessarily a good solution. This is because the operation of the LNG carrier is based on the interrelationship between all the components to deliver the volume of cargo according to a signed contract and on time. Reducing the speed and size of the vessel will end up with an increase in fleet size, which might result in more emission products. Another way to minimise the fuel consumption is by using a higher thermal efficiency engine.

Basically, the emission product is a function of the total power requirement to run the ship according to its mission profile, Specific Fuel Consumption (SFC), and Pollutant Emission Ratio (PER), as shown in Figure 5-1.

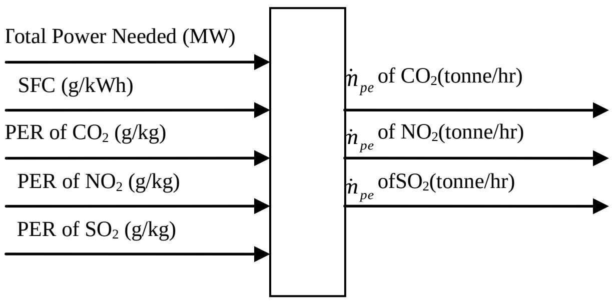


Figure 5-1: The Inputs and Output of the Emission Pollutant Model

The emission products are qualified in term of the Specific Pollutant Emission (SPE) and Pollutant Emission Ratio (PER). Specific Pollutant Emission is the mass flow rate of pollutant emissions ($\dot{m}_{pe}$) divided by the brake power of the engine (P_B) (Woud and Stapersma, 2002). The Specific Pollutant Emission can be written in mathematical form as:

$$SPE = \frac{\dot{m}_{pe}}{P_B}(kg/Ws)$$

The Pollutant Emission Ratio is the mass flow rate of pollutant emission ($\dot{m}_{pe}$) divided by the mass flow rate of the fuel ($\dot{m}_f$), in mathematical form it is given by:

$$per = \frac{\dot{m}_{pe}}{\dot{m}_f}(g/kg)$$

The Specific Pollutant Emission can also be obtained by multiplying the PER with the SFC:

$$spe = \frac{\dot{m}_{pe}}{P_B} = \frac{\dot{m}_{pe}}{\dot{m}_f} \cdot \frac{\dot{m}_f}{P_B} = per \cdot sfc$$

From the above equation, $\dot{m}_{pe}$ is the product of PER, SFC and P_B. In this study, the unit of mass flow rate of the pollutant emission is in tonnes per hour of the amount of emission product produced by a single ship. Although the pollutant emissions cannot be eliminated due to the source of energy used to produce motive power, which comes through the burning of fuel, overall optimisation of the system will however minimise these emissions.

Appendix 6

Mathematical Modelling of Ship Steel Weight

There are many materials that have been used to build the hull structures of ships, e.g. steel, aluminium and glass-reinforced plastic (Eyres, 2007). All of these materials have their own characteristics, however, the selection of the materials for the building for a particular ship are highly dependent on the strength of the materials in order to support the forces and stresses produced by six degrees of wave-induced ship motions, and their ability to withstand corrosion due to the chemical reactions with seawater (Schumacher, 1979). This is to minimise the overall material weight of the ship, to reduce the costs of ship construction, and for ease of fabrication and maintenance of the ship's structures (Rawson and Tupper, 2001).

Currently, the hulls of the entire world-wide fleet of LNG carriers are made from various grades of steel. Since the costs of material to build the ships are based on the weight of the steel used in the construction, it is no surprise that the calculation of the ship steel weight is an important element in the ship design process, due to its contribution to the estimation of the capital cost of the ship. The size of the ship obviously influences the ship steel weight, because the size has a directly proportional relationship with the weight. The larger the ship being constructed, the heavier the weight of the ship will be, thus it will affect the total displacement and the ship's hydrodynamic resistance, which will finally result in an additional machinery power requirement to propel the ship according to a given mission profile.

In an LNG carrier, the hull steel weight refers to the quantities of steel used to manufacture the ship. The quantities of steel used include plates, rolled sections, castings and weld metal (Schneekluth and Bertram, 1998). The weight of the steel not only refers to the steel plate and varies according to the size of the vessel. It is only once the detailed design stage is reached that, with the aid of a CAD system, weight may then be calculated with a reasonable degree of accuracy. However, many studies have been conducted in the past regarding this subject including those of Watson and Gilfillan (1976), Liu et al. (1981), and Schneekluth and Bertram (1998).

Although, there are many methods to estimate the ship steel weight at an early stage in the design process, among common variables for this calculation are overall length, breadth, capacity and steel cost as shown in Figure 6-1.

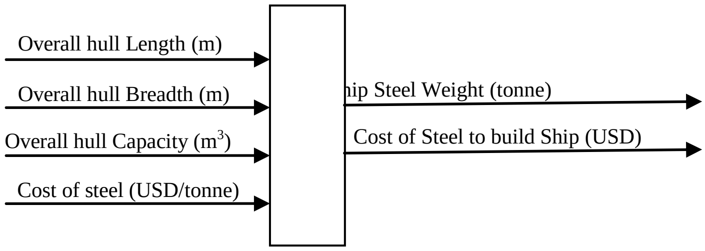


Figure 6-1: The Inputs and Outputs of the Ship Steel Weight Estimation Model

In this thesis, the formulation to estimate ship steel weight is based on a DetNorsekeVeritas method from 1972 (Schneekluth and Bertram, 1998). The estimate of the ship steel weight is given by:

$$W_{St} = \Delta[\alpha_L + \alpha_T(1.009 - 0.004\cdot(L/B))\cdot 0.06\cdot(28.7-(L/D))]$$

Where:

W_{St} is weight of the ship steel in tonnes

Δ is displacement of the ship in metres cube

α_L is $[(0.054+0.004L/B)\cdot 0.97]/[0.189\cdot(100L/D)^{0.78}]$

α_T is $0.029+0.00235\cdot\Delta/100000$

L is length in metres

B is breadth in metres

Once the estimation of the cost of the steel covering both material and man hours to build the ship has been calculated, it can then be linked with the capital costs section in the life cycle cost analysis. Since the components of an LNG carrier are interrelated with each other, the ship steel weight estimation can only be determined when all of the full systems of components have been evaluated. An iterative process may be required in order to progressively refine the estimates.