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LNG-fuelled fishing vessels: a systems engineering approach

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Abstract

Air emissions from fishing vessels must be reduced to comply with progressively tightening environmental regulations. Among the available solutions, liquefied natural gas (LNG) fuel may represent a promising solution, particularly from an environmental perspective. However, the use of LNG as a marine fuel creates different types of hazards than those that exist for traditional fuels. In addition, the higher complexity, safety requirements, and space needed for LNG installation increase the capital cost. This article uses a systems engineering approach to clarify the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed to operate them safely. Ship owners can use such an approach to aid decision-making and trade-off analyses. Naval architects may also benefit from better information management. Finally, the crew may better understand the logic behind the safety actions they are instructed to take.

Keywords

LNG; Fishing vessel; Ship design and operation; Systems engineering; Safety; Cost

1 Introduction

Except for airborne transportation, fishing vessels are responsible for the largest portion of the energy consumed in and emissions resulting from the seafood product value chain (Avadí and Fréon, 2013; Parker et al., 2015; Winther et al., 2009). Although considerable differences in energy efficiency exist among different types of fishing vessels (Jafarzadeh et al., 2016), since 1990, global fisheries have consumed a median value of 639 litres of fuel per tonne of fish (Parker and Tyedmers, 2015). In 2000, fishing vessels accounted for approximately 1.2% of worldwide oil consumption and produced 134 million tonnes of carbon dioxide (CO_2). These values are likely underestimates, given that energy inputs for the provision of fuel, vessels, and fishing gears were not considered (Tyedmers et al., 2005). Furthermore, the CO_2 estimate only accounts for emissions from energy use and excludes greenhouse gas (GHG) emissions from refrigerants on board (FAO, 2012). Hence, the regulations imposed on fishing vessel emissions have become increasingly strict. In 2011, the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI was revised to control GHG emissions by introducing the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2013a). The EEDI does not currently apply to fishing vessels, but it may apply in the future (Bazari and Longva, 2011). The SEEMP applies to fishing vessels of 400 GT and above (Hop, 2016). Additionally, the Kyoto Protocol covers domestic shipping and regulates GHG emissions in Norway and other involved countries. In 2012, this protocol was revised to set new caps (UNFCCC, 2014).

Because fishing vessels emit sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) (Lin and Huang, 2012), the MARPOL Annex VI regulations also aim at reducing these emissions globally and more stringently in emission control areas (ECAs). These regulations apply to all ships. Vessels of 400 GT and above require an International Air Pollution Prevention (IAPP) Certificate to demonstrate their compliance with these regulations. The Flag Administration may establish other measures to ensure the compliance of smaller vessels (DNV, 2008; Hop, 2016; IMO, 2013b). Additionally, the Gothenburg Protocol regulates NO_x emissions in Norway and other involved countries. In 2012, this protocol was revised to set caps for 2020 (UNECE, 2014).

To fulfil the NO_x cap, Norway introduced a NO_x tax and a fund that applies to domestic shipping and fishing. The Norwegian state and 15 business organizations (e.g., the Norwegian Fishermen's Association) signed a NO_x agreement, which means that the organizations will adopt emission-reducing measures and pay a smaller amount to the NO_x fund instead of the NO_x tax. The fund supports measures that reduce NO_x (EFTA, 2011; Høibye, 2012; NHO, 2013; Åsen, 2013).

In Norwegian waters[1], fishing vessels contributed to approximately 10.2% of the fuel consumed by ships in 2013 (DNV GL, 2015b). Compared to passenger ships (22.3%) and offshore supply vessels (15.7%) (DNV GL, 2015b), fishing vessels were the third most fuel-intensive shipping segment in Norway. Fuel is one of the primary costs associated with fishing, and the proportion of the cost that it represents varies among fisheries (Sumaila et al., 2008). Various factors affect fuel consumption and fuel cost, such as the target species and harvesting method. For example, in 2012, fuel and lubrication oil accounted for approximately 5–38% of the operational costs for Norwegian shrimp trawlers, whereas the mean value for the entire fleet was 10% (these calculations were based on a dataset from the Directorate of Fisheries (2014)). In addition, seafood consumers are becoming aware of the environmental consequences of fishing, and the environmental impact of seafood products may influence the market share (Fet et al., 2010).

Regulations and agreements act as incentives to reduce emissions from fishing vessels and develop greener fisheries. Ship owners have different options regarding compliance with the regulations (Jafarzadeh et al., 2012; Martelli et al., 2016; Notti and Sala, 2013). Among these options, the use of liquefied natural gas (LNG) as an alternative fuel is gaining increasing attention, particularly from an environmental perspective (Benvenuto et al., 2013; DNV, 2011; LR, 2012). However, the use of LNG as a marine fuel creates different hazards than traditional fuels, such as cryogenic temperatures and increased fire intensity, creating an explosion risk. To ensure safety, it is necessary to consider different and/or additional safeguards when using LNG (Davies and Fort, 2013). In addition, the higher complexity, safety requirements, and space needed for LNG installation increase the capital cost of LNG-fuelled vessels compared to their oil-fuelled counterparts (Chryssakis et al., 2015; Tzannatos et al., 2015). Lower operational expenses should compensate for the additional investment costs to ensure profitability.

Powering fishing vessels with LNG may be a solution for reducing air emissions from the fleet (Altosole et al., 2014; Danish Maritime Authority, 2012); however, environmental improvements should not come at the cost of safety and profitability; otherwise, the ship owners may prefer other solutions over LNG. The objective of this article is to present a systematic approach for a feasibility analysis of LNG in the fishing fleet and thus increase knowledge regarding the requirements, costs, and benefits of LNG-fuelled ships for the ship owners, naval architects, and crew. A systems engineering (SE) process is used to clarify the technical aspects of LNG-fuelled systems, their potential implementation costs, and the expertise and training needed to operate them safely. Ship owners can use this knowledge in parallel with other decision-making processes to determine whether LNG fuel is the appropriate choice. They may also use this approach to plan for harnessing the environmental benefits of LNG without exposing the crew and fishing vessels to higher risk.

The remainder of this article is organized as follows. A brief background on LNG as a marine fuel is presented in Section 2. Then, Section 3 presents the SE and the systematic approach to LNG implementation. Section 4 provides details via an analysis of a shrimp trawler. Section 5 presents a discussion of the results, and Section 6 presents the conclusions.

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[1] Norwegian waters include the Norwegian economic zone, fishery protection zones around Svalbard and Jan Mayen Islands, the Loop Hole (i.e., Smutthullet) in the Barents Sea, and the Banana Hole (i.e., Smutthavet) in the Norwegian Sea (DNV GL, 2015b).

2 LNG-fuelled vessels

Natural gas, which is mainly methane, liquefies at -160°C, and its volume is reduced to 1/600 of its gaseous state, thus making it more space efficient for storage and transportation on ships (Wang and Notteboom, 2014). There is extensive experience with LNG use in terms of the use of boil-off gas in LNG carriers. Since 2000, other vessel types, such as ferries and offshore supply vessels, have also used LNG fuel (Chryssakis et al., 2015). Three engine types can use LNG as fuel (Einang, 2013):

- Pure gas engines or lean-burn spark-ignited gas (LBSI) engines
- Low-pressure dual fuel (LPDF) engines
- High-pressure dual fuel (HPDF) engines

LBSI engines use only gas, whereas LPDF and HPDF engines can run on both gas and diesel fuel. LBSI engines operate on the Otto cycle, in which a spark plug initiates the combustion process. LPDF engines operate on the Otto cycle in gas mode, in which pilot fuel oil starts the combustion process. The gas supply pressure is low in both LBSI and LPDF engines, with pressures of approximately 5–6 bar for four-stroke engines and 10 bar for two-stroke engines. Therefore, gas can be provided either directly from a pressurized storage tank or by a compressor. HPFD engines use the diesel cycle in gas mode. Gas is injected at high pressure into the cylinder (i.e., approximately 300 bar) after the pilot fuel oil has ignited. An additional high-pressure gas compressor or a LNG pump is needed to provide such a high pressure. In addition, special piping and a safety system are required (Boulougouris and Chrysinas, 2015; DNV GL, 2015a; Æsøy et al., 2011).

In March 2016, 77 LNG-fuelled ships were in operation, and 85 new ships were under construction, with planned deliveries within 2022. These numbers exclude LNG carriers and inland waterway vessels. Of the operating vessels, 69% operate in Norway (DNV GL, 2016). LNG-fuelled vessels may potentially reduce emissions, but several aspects are important during the design and operation phases, which are discussed in the following sub-Sections.

2.1 Environmental aspects

LNG-fuelled ships emit almost no SO_x and PM; LNG emits up to 90% less NO_x compared to heavy fuel oil due to the lower peak temperature of combustion. The amount of NO_x emissions depends on the engine design: a pure gas Otto cycle engine can comply with the most stringent NO_x cap, whereas a gas engine based on a diesel cycle, which uses oil pilot ignition, cannot comply. Nevertheless, the latter still emits less NO_x than conventional oil-fuelled engines. LNG emits approximately 25% less CO_2 than conventional engines due to its higher hydrogen-to-carbon ratio compared to diesel (LR, 2015; Wang and Notteboom, 2014).

Methane has a stronger GHG effect than CO_2 and can leak during the production, transportation, and use of natural gas. Such leakage can offset some of the benefits gained from switching to LNG from a lifecycle perspective (Bengtsson et al., 2011; Brynolf et al., 2014; Buhaug et al., 2009; DNV, 2011; LR, 2015). Most LNG-fuelled engines operate on the Otto cycle, which results in a methane slip of 2–3%. A total methane leakage of 5.5% during the entire life cycle would cause the GHG emissions from LNG to be equivalent to the corresponding value for diesel fuel (Chryssakis et al., 2015).

2.2 Economic aspects

Newly built LNG-fuelled ships require 20–25% more capital investment compared to oil-fuelled vessels (Wang and Notteboom, 2014). The cost range depends on ship design, engine type, and fuel tank size, among others. Converting an existing vessel is even costlier. Therefore, LNG appears more feasible for newly built ships (Wang and Notteboom, 2014). LNG tanks are one of the largest capital expenses for LNG-fuelled vessels (DNV

GL, 2014). The vacuum-insulated C-type tank is the most commonly used of the tank types available[2] (Rolls-Royce, 2016). For a similar energy content, LNG requires approximately 1.8 times larger tanks compared to marine gas oil (MGO). When adding tank insulation and considering a maximum filling ratio of 95%, this difference is approximately 2.3 fold. Among other components, additional bulkheads, void spaces, access trunks, and vents increase the difference to 3–4 fold (Bagniewski, 2010; Kraack, 2014). In addition, restrictions on the location of LNG tanks exist for safety reasons. For instance, whereas MGO can be stored in wing tanks, LNG tanks are distanced from shipside by B/5[3] or 11.5 m, whichever is less (IMO, 2015b). Therefore, LNG tanks occupy space that could be used for other purposes, such as a fish hold or cargo. LNG tanks are also costly because they must be constructed from materials suitable for cryogenic temperatures (e.g., stainless steel) and require insulation (Boulougouris and Chrysinas, 2015).

Lubrication oil in pure gas engines does not become contaminated, and purifiers and oil changes are typically not required. Gas engine rooms also stay considerably cleaner than conventional engine rooms, which leads to lower maintenance (Rolls-Royce, 2016). However, specially trained crew is needed because a gas system is more complex than a conventional system. The complexity also adds to the cost of spare parts (Mohn, 2012). Components are costlier for high-pressure gas supply systems compared to their low-pressure counterparts. In addition, more energy is consumed to produce high pressures, leading to higher costs (WinGD, 2015).

Although there are different views regarding the future price of LNG, the majority of studies are optimistic about its future price advantage (Wang and Notteboom, 2014). Possible fuel or emission taxes, such as the NO_x tax in Norway, can increase economic interest in LNG. Solving current bunkering problems can also foster its adoption (DNV, 2011; Wang and Notteboom, 2014).

2.3 Safety aspects

The development of the LNG supply chain in Europe (EIA, 2013) has led to several studies on risks related to LNG handling. For instance, Cozzani et al. (2011) identified and analysed accident scenarios related to LNG handling. Tugnoli et al. (2010) and Paltrinieri et al. (2015) warned about the presence of potential hazards and risks posed by new LNG technologies, which may be well known to academics but are ignored by professionals. In addition to the potential for fires and explosions (e.g., pool fires, a vapour cloud explosion, and flash fires), a series of hazards resulting from the specific properties of LNG have been reported, such as:

- Rapid phase transition: a phenomenon occurring when the temperature difference between a hot liquid and cold liquid is sufficiently large to drive the cold liquid rapidly to its superheat limit, resulting in spontaneous and explosive boiling of the cold liquid (Reid, 1983).
- Cryogenic burns and cryogenic damage: hazards due to the cryogenic temperatures of LNG (Woodward and Pitblado, 2010).
- Asphyxiation: immediately after the release of LNG, a dense vapour cloud forms around the area of the spill close to the ground, leading to an asphyxiation hazard (Woodward and Pitblado, 2010).

The world LNG carrier fleet has implemented LNG risk management (Chryssakis et al., 2015). However, the majority of the world fleet, including fishing vessels, has no experience with handling LNG. This segment regards alternative fuels for economic and environmental benefits, but managing risk related to new potential accident scenarios might be challenging (Chryssakis et al., 2015). Fishing vessels are dangerous work environments, as demonstrated by Lindøe (2007), who compared the fatal accident rates of the fishing and

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[2] For an overview of tank types, see Boulougouris and Chrysinas (2015).

[3] “B is the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught) (refer to SOLAS regulation II-1/2.8)” (IMO, 2015b).

offshore petroleum industries from 1990 to 2005. The fatality rate of fishermen was 12-fold higher than the corresponding value for offshore workers on average. If helicopter accidents are excluded, this difference increases to 25 fold. Several factors may explain the higher fatality rate in fishing compared to offshore industry. McGuinness et al. (2013) state that the main fatality modes in Norwegian fisheries are vessel accidents (e.g., collisions, groundings, foundering, capsizing) and man overboard. However, we aim to address the overall safety strategy in the sector. In fact, one explanation for this gap in safety levels may be the different competence of the workforce and safety management systems (Lindøe, 2007). Despite a recent decrease in its fatal accident risk, fishing is still the occupation in Norway most exposed to risk (McGuinness et al., 2013). Switching to LNG must not make fishing even more dangerous.

Safety must be built into the system, and safety during operation depends both on the design and effective operational control. Ship owners and fishing vessel crew may not be familiar with the safe handling of LNG. Everyone involved in the operation must understand their responsibility and the safety rationale behind the system design. If the crew understand the purpose of the safety programmes, they are more likely to commit to them. Understanding the safety rationale will also foster the avoidance of unintended system changes that lead to hazards (Leveson, 2011).

3 A SE approach to the design and safe operation of LNG-fuelled ships

Verification of the technical and operational aspects of LNG-fuelled systems and their potential implementation costs and benefits is a challenging decision problem with an interdisciplinary nature. A SE approach is used to address this problem. Classical engineering practices typically deconstruct a system to its formative elements to aid understanding. However, systems thinking prioritizes the study of a system as a whole. It recognizes system level behaviours, interactions, and structural characteristics that are missed by focusing on individual elements instead of “the big picture” (Driscoll, 2010). For instance, safety is a system property, not a component property. As such, safety must be controlled at the system level, not at the component level. Systems thinking may assist in understanding system dynamics and preventing system accidents (Leveson, 2004, 2011).

A SE approach starts with the desired goal of the system and stakeholder requirements. Then, it identifies system functions, processes, structures, and elements that can fulfil the desired goal (Driscoll, 2010). The approach suggested in this article and shown in Figure 1 is based on Dahl (2001) and Oliver et al. (1997). The process has been adapted to fishing vessels and LNG in particular. It comprises six sequential steps and one iteration loop, with input from INCOSE (2015), Kossiakoff et al. (2011b), Long and Scott (2011), and Sproles (2001, 2002):

1. The process begins with understanding the problem and highlighting its importance.
2. Next, relevant information that may help solve the problem is compiled. Available information may be in different forms (e.g., text, models, and stakeholder knowledge).
3. Early in the process, measures of effectiveness (MOEs) are defined. MOEs are a subset of the requirements imposed on the system. They are the yardsticks used to assess alternative solutions, and success of a system depends on their fulfilment. These measures are useful for assessing complete systems and may also be used as monitoring tools in the early and late phases. For example, they can monitor progress during the system development process. They can also monitor the system through its lifetime to verify whether it still fulfils the needs for which it was designed.
4. In the next step, the user requirements, behaviour, and structure of the system are clearly defined. Model-based systems engineering (MBSE) is used to capture, investigate, share, and manage the available information. Using models, MBSE supports system requirements, design, analysis, verification, and validation during various life cycle phases, such as the conceptual design phase. The MBSE approach consists of three parts. Each part views the system from a different perspective:
    - First, the requirements imposed on the system are organized. The *requirement analysis* model is a hierarchy that starts from the source documents and ends in system components. It aims at

clear identification and traceability between documents, requirements, functions, processes, and the system components.

- Next, the functions that the system must perform to fulfil the requirements are identified, i.e., *functional behaviour*. This model orders functions into processes by looking at their sequence and how inputs (e.g., the occurrence of unwanted events) activate functions.
- Finally, the functions are translated into the hardware and software components that are necessary to carry out the functions. The *architecture* model breaks the system down into its components, both physically and logically, and delineates their relationships. In the concept development stage, such a model can help to embody the system concept and provide a tangible and physical form for the system to be built. It can make the system more understandable for its stakeholders.

5. Once the alternative architectures or designs have been created, a trade-off analysis uses stakeholder-defined criteria (i.e., the MOEs) to evaluate and compare system designs. The aim is to identify the system design that most closely matches the stakeholders' objectives.
6. When a feasible and near-optimal architecture has been identified, an implementation plan is produced.

When necessary, iteration is performed back to Step 2. The approach and its steps are demonstrated for a fishing vessel in the following section.

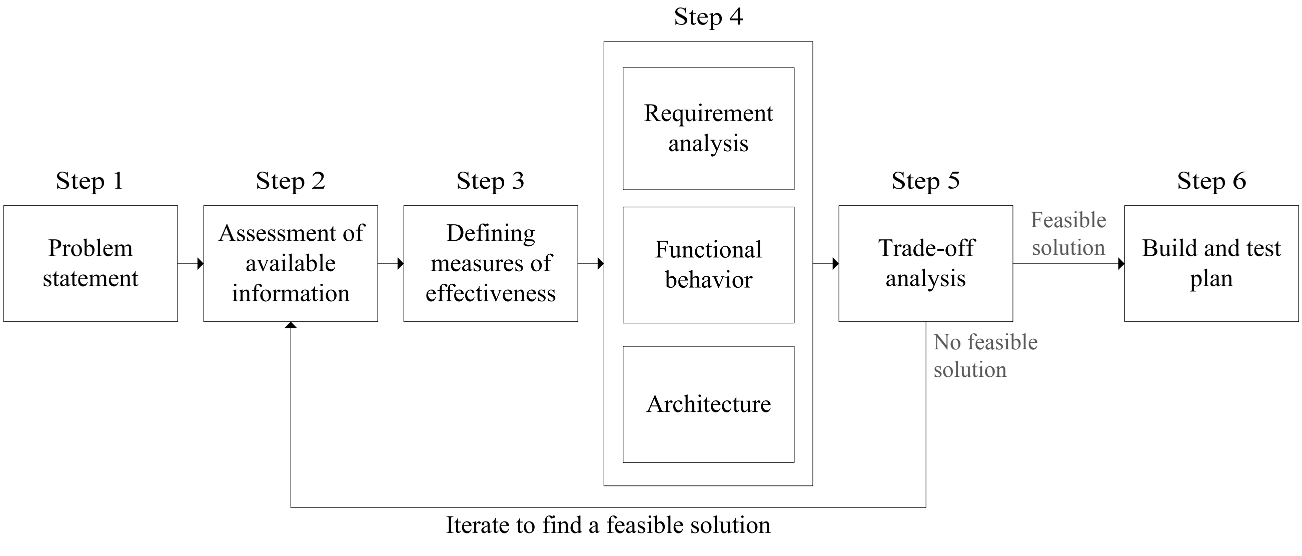

Figure 1: Modified SE process (adapted from Dahl (2001); Oliver et al. (1997))

4 Application to fishing vessels with LNG propulsion

4.1 Step 1 - Defining the problem

The use of LNG on energy-demanding vessels with high catch and regular coastal routes, such as coastal demersal trawlers in Norway, appears more environmentally and economically attractive for several reasons (DNV, 2012; Jafarzadeh et al., 2016; Jafarzadeh et al., 2012; Winther et al., 2009):

- Natural gas and bunkering stations are available in Norway.
- It is easier to predict fuel consumption for vessels with specific routes. It also makes the vessels reliable and provides regular customers for bunkering stations.

- Coastal vessels require smaller LNG tanks and can allocate more space to fish holds.
- Demersal trawlers consuming a considerable amount of energy and produce considerable pollution.
- The Norwegian NO_x tax and fund system promotes switching to LNG propulsion.
- Extreme cold from the LNG regasification process can be recovered for cargo cooling, and thus, fuel consumption and associated emissions can be reduced in this manner.

Technology transfer of LNG-fuelled propulsion from other types of vessels (e.g., offshore oil and gas supply vessels) to fishing vessels may be relevant but requires re-innovation (i.e., "adaptations to use") to make the technology operable in the new context of fishing. In addition, a mere technology transfer is not adequate; competence and knowledge regarding the technology must also be fully transferred, which may be challenging (Olsen and Lindøe, 2009).

4.2 Step 2 - Relevant information for building and operating the system

4.2.1 System boundaries

The system in this study consists of the technical, operational, and economic aspects of a LNG-fuelled fishing vessel. Technical aspects range from the components (e.g., pressure relief valves) to design considerations (e.g., collision distance between the LNG unit and shipside). Operational aspects range from the daily tasks of the crew, including maintenance, to emergency preparedness and handling. Economic aspects cover capital and operational costs and benefits. From a SE perspective, operators and stakeholders are parts of the system environment imposing interface requirements that must be satisfied by the system.

A context diagram is a communication tool that depicts the system, its environment, and the interactions between them (Kossiakoff et al., 2011b). This diagram does not depict the internal details of the system. Instead, it highlights the external factors that may be relevant to the system's operation, and should thus be considered while developing the system. It is a starting point for defining the system's mission and operating environment. The interactions between the system and environment show system inputs and outputs in the form of receiving and sending data, signals, material, and energy or an action that affects the system or environment. Relevant information about these interactions should be compiled (Kossiakoff et al., 2011a, b; Oliver et al., 1997).

The system environment includes different stakeholders, such as the ship owner, crew, bunkering station, material suppliers, equipment manufacturers, and naval architect. Figure 2 is a reduced context diagram. For example, the ship owner may have specific requirements regarding the space and arrangement needed for the fishing gear and fish holds. However, the system may impose requirements on the location and size of the LNG tanks, among other things. Considering all of these requirements, the gas system should be optimized to avoid interference with normal operation of the vessel. The economic implications of these requirements should also be evaluated. As another example, the crew has specific duties, such as navigating the vessel or handling the fishing gear. However, the system requires some routine and emergency operations for the safe handling of the LNG. LNG-related training should consider normal fishing operations. The cost of various training schemes should also be evaluated.

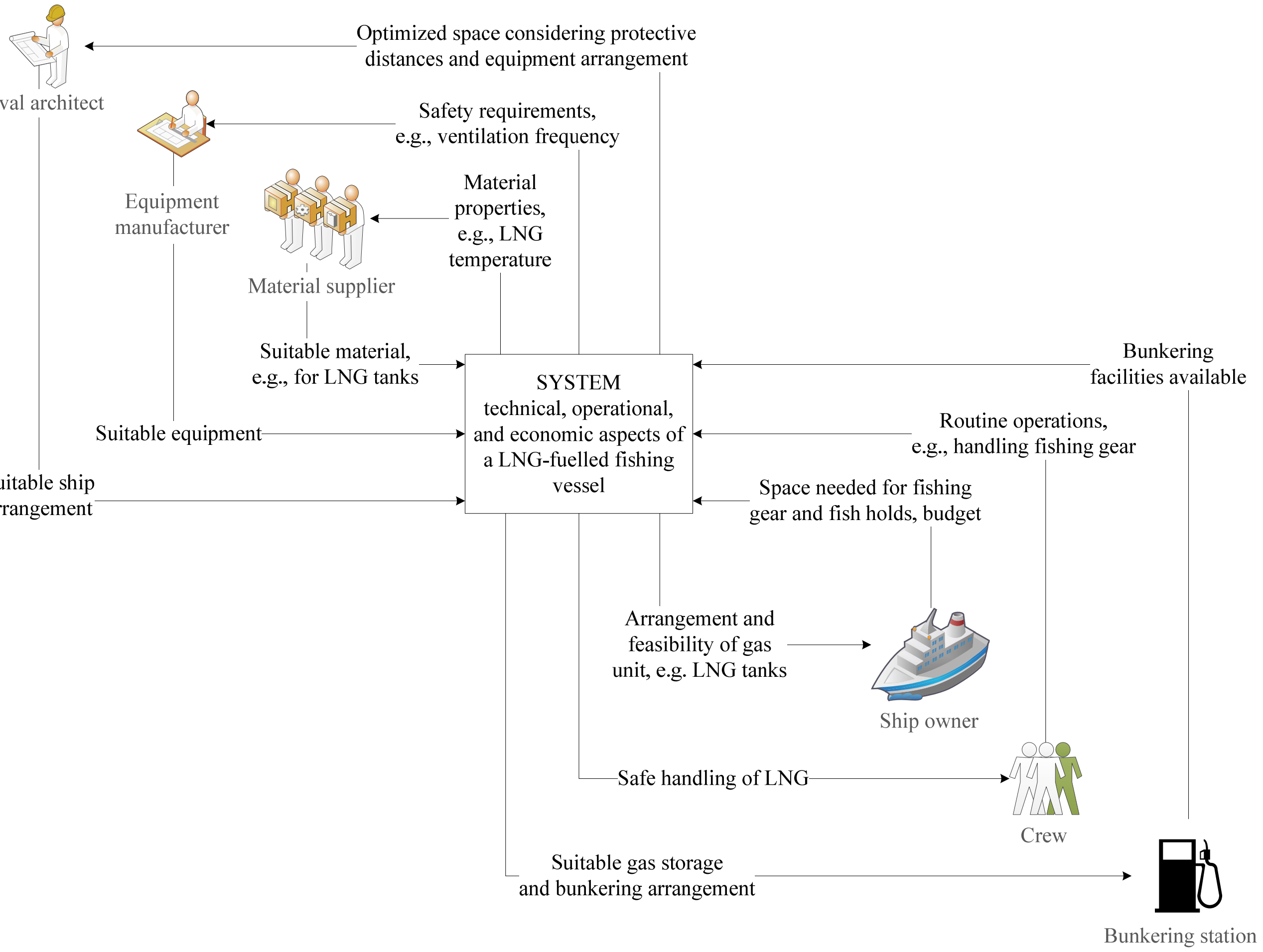

Figure 2: Reduced context model

4.2.2 Regulatory framework

Because the technical and operational aspects of a LNG-fuelled fishing vessel are part of the system, the regulations and guidelines that address the design and operation of LNG-fuelled ships are relevant information. These regulations also have cost implications because they impose additional requirements, such as the installation of gas detectors and safety training.

In June 2015, the International Maritime Organisation (IMO) adopted the mandatory International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). The IGF Code will come into force in 2017. Until then, the Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships have been adopted. Concurrently, Regulation V/3 was added to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). Similarly, Section A-V/3 was added to the STCW Code and includes new compulsory minimum requirements for the training and qualification of personnel on ships subject to the IGF Code[4]. These amendments will also come into force in 2017 (Danish Maritime Authority, 2015; IMO, 2015a, b).

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[4] The STCW Convention consists of three sections: (i) the articles, which outline the legal responsibilities of the involved parties, (ii) the annex, which provides technical details on how the responsibilities mentioned in the articles should be met, and (iii) the STCW Code, which specifies the technical details contained in the annex (ITF, 2013).

The IGF Code mainly addresses the technical requirements for LNG-fuelled ship design. However, it also addresses operations, drills and emergency exercises. For example, it requires that the IGF Code and maintenance procedures be provided on board the vessels. Section A-V/3 of the STCW Code addresses the training and qualifications of the crew in greater detail. It identifies two levels of training, basic and advanced based on personnel's responsibilities (IMO, 2015c).

Both levels of training require some knowledge of the IGF Code. Among other things, basic training requires basic knowledge on ships subject to the IGF Code, fuel systems, and fuel storage systems. It also requires an understanding of safety requirements and safety management on these ships. The advanced training, among other things, requires an understanding of the hazards and control measures associated with fuel system operations. In addition, it demands proficiency in the use of the IGF Code (IMO, 2015d). Therefore, the technical and operational regulations are closely linked, and the crew should understand how safety is built in the system to operate it properly.

In addition to these binding regulations, other organizations provide relevant information on the safe operation of LNG carriers or LNG-fuelled ships. For instance, the Society of International Gas Tanker and Terminal Operators (SIGTTO) specifies and promotes best practices to maintain confidence in the safety of the liquefied gas industry. Among other things, SIGTTO publishes guidelines for safe cargo handling on LNG carriers (SIGTTO, 2014). In 2013, the Society for Gas as a Marine Fuel (SGMF) was established. SGMF is a non-governmental organization that promotes safety and industry best practices for the use of gas as a marine fuel. Among other things, it publishes safety guidelines for LNG bunkering (SGMF, 2016).

4.2.3 Environmental taxes and fund

In Norway, a fishing vessel with a total engine power of more than 750 kW operating within 250 nm (nautical miles) offshore is liable to be taxed on NO_x emissions. Although vessels in direct traffic between Norwegian and foreign ports are exempted from the tax, a vessel will not be considered in direct traffic if engaged in fishing during the course of the voyage (Directorate of Customs and Excise, 2015; Norwegian Maritime Directorate, 2014).

The tax rate in 2016 is 21.17 NOK (2.45 USD)[5] per kg NO_x (Skatteetaten, 2016). If the vessel adopts a NO_x reduction measure, such as LNG fuel, it can pay a lower rate to the NO_x fund instead of the NO_x tax. As of 2016, the reduced rate is 4 NOK (0.46 USD) per kg NO_x for fishing vessels (NHO, 2016b).

In addition, the NO_x fund provides financial support for NO_x reduction measures. The support rate varies for different measures. In 2016, the support for LNG-powered ships is 375 NOK (43.35 USD) per kg NO_x reduced. This support is limited to 80% of the additional cost for the measure (NHO, 2016a).

Norwegian fishing vessels either are exempt from the basic tax on mineral oil or have the tax refunded (i.e., "grunnavgift" in Norwegian). Fishing in distant waters is also exempt from CO_2 and SO_x taxes in Norway. However, fishing in Norwegian coastal waters (i.e., within 250 nm ashore) is subject to 0.28[6] and 0.133[7] NOK (0.03 and 0.02 USD) per litre of MGO for CO_2 and SO_x emissions, respectively. LNG-powered fishing vessels are exempt from these taxes (GFF, 2016; Norwegian Directorate of Taxes, 2016).

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[5] NOK and USD respectively stand for Norwegian Krone and US Dollar. An average 2016 exchange rate (1 USD ≈ 8.65 NOK) is considered (Norges Bank, 2016).

[6] Upon bunkering, coastal fishing vessels pay 0.92 NOK/L (0.11 USD/L) for the CO_2 tax. Later, they can be refunded for 0.64 NOK/L (0.07 USD/L). Therefore, the net value paid is 0.28 NOK/L (0.03 USD/L) (GFF, 2016).

[7] The SO_x tax depends on the sulphur content of the fuel. This rate applies to mineral oils with 0.05–0.25% sulphur.

4.3 Step 3- Measures of effectiveness

The goal of the IGF code is "to provide for safe and environmentally friendly design, construction, and operation of ships and, in particular, their installations of systems for propulsion machinery, auxiliary power generation machinery and/or other purpose machinery using gas or low-flashpoint fuel as fuel" (IMO, 2015b). The main purpose of the STCW Convention is "to promote safety of life and property at sea and the protection of the marine environment by establishing in common agreement international standards of training, certification and watchkeeping for seafarers" (IMO, 2016). If a candidate solution cannot comply with these, it should be rejected. For this reason, the following MOE has been defined:

- Compliance with safety requirements

Implementing safety measures can reduce the risk of severe accidents and improve safety. However, these measures incur cost and may be reduced by the stakeholders to minimum protections. On the other side, LNG has the potential to reduce the operational cost (see Section 2.2). As a result, the following MOE is also considered:

- Life cycle cost (LCC)

The new system should meet the functional requirements at a reasonable cost over its anticipated lifetime. The system life cycle includes various stages, ranging from conceptualization and design to operation and system retirement (Pohl and Nachtmann, 2010). In many cases, it may not be necessary to perform a complete LCC analysis. Instead, an estimation of the major cost elements is sufficient (Norsok Standard, 1996).

As a minimum, these MOEs should be considered while evaluating an LNG solution. Stakeholders may also consider other MOEs.

4.4 Step 4 - Model-based SE

Various requirements are imposed on the system. Some requirements, such as those imposed by the IGF Code, are related to technical requirements. Others, such as those imposed by Section A-V/3 of the STCW Code are operational (see Section 4.2.2). In addition, there may be financial requirements. For instance, ship owners may require a specific payback time for a LNG investment. Although models can be established based on all of these requirements, the remainder of this sub-Section focuses on models based only on technical and operational requirements.

4.4.1 Requirement analysis

The IGF Code, Section A-V/3 of the STCW Code, and the SIGTTO guidelines are the main sources for the requirement analysis model, which is illustrated in Figure 3. Although the SIGTTO guidelines mainly address the safe operation of LNG carriers, they may be relevant to the operation of LNG-fuelled ships, such as SIGTTO (2000, 2002, 2011). Other sources (e.g., port regulations and national laws) may impose additional requirements on the system in specific cases.

The IGF Code addresses "provisions for the arrangement, installation, control, and monitoring of machinery, equipment, and systems using low-flashpoint fuel". Section A-V/3 of the STCW Code covers the "minimum requirements for the training and qualifications of the masters, officers, ratings, and other personnel on ships subject to the IGF Code". These two form the upper hierarchy guidelines in the requirement model, as illustrated in Figure 3.

These guidelines are divided into four primary safety-related requirements, as shown in Table 1. These requirements are not comprehensive; other requirements may be added to the list based on the IGF and STCW Codes. Each of the primary requirements includes several secondary requirements, which trigger different barrier functions in the system. Barrier functions specify the tasks or roles of barriers (PSA, 2013).

The system requires various barrier elements, i.e., measures or solutions that are instrumental in fulfilling a barrier function (PSA, 2013). The requirement analysis model links the requirements to the corresponding barrier functions and barrier elements.

For example, regarding Figure 3, Primary requirement 1 includes several secondary requirements, such as "*Minimize the probability of damage to fuel tanks and piping*". Different barrier functions are needed to satisfy this secondary requirement, such as "*Protecting tanks and pipes against collision, grounding, and mechanical damage*". Different technical and operational barrier elements carry out this barrier function, such as "*Specified minimum distances from the ship shell plating […]*".

Table 1: Primary requirements based on the IGF Code and Section A-V/3 of the STCW Code

Primary requirement	**Definition**	**Number tag used in bowtie diagrams (Figures 5 and 6)**
1	Prevent leakage and overpressure in the gas fuel storage, bunkering arrangement, and gas piping system.	1
2	Contain leakage and/or reduce overpressure to the highest extent.	2
3	Prevent fire and explosion in the fuel containment and machinery space.	3
4	Mitigate accident consequences.	4

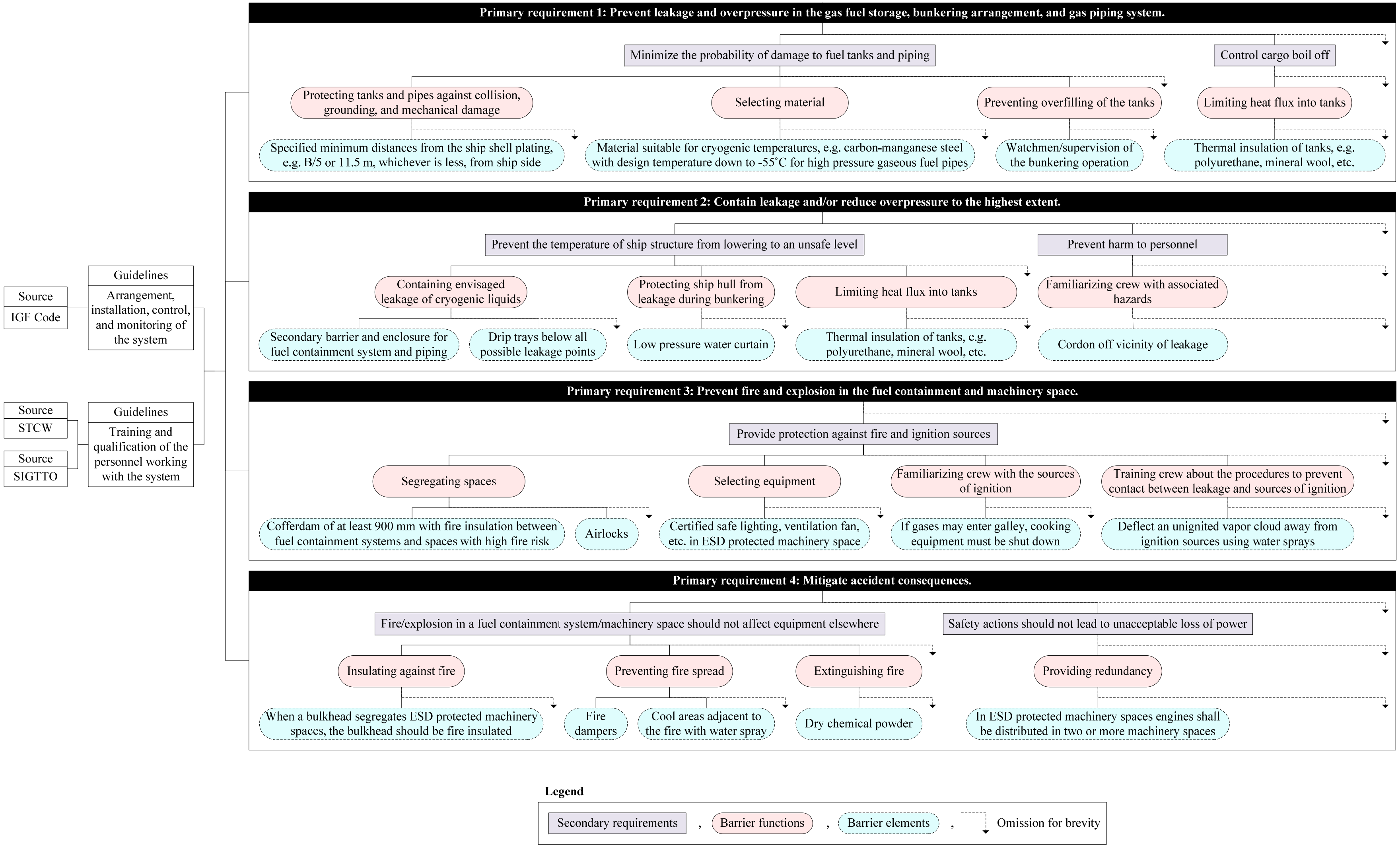

Figure 3: Reduced requirement analysis based on IMO (2015b, 2015d); SIGTTO (2000, 2002, 2011). “Breadth (B) means the greatest moulded breadth of the ship at or below the deepest draught (summer load line draught)” (IMO, 2015b).

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4.4.2 Functional behaviour

Figure 4 illustrates some representative elements of the functional behaviour model. Primary requirement 1 and its barrier functions are in place to prevent leakage and overpressure. If these functions are not successful in meeting this requirement, Primary requirement 2 and its barrier functions address the occurrence of leakage and/or overpressure. If leakage cannot be controlled, Primary requirement 3 and its barrier functions prevent fire and explosion. If these functions also fail, Primary requirement 4 and its functions minimize accident consequences.

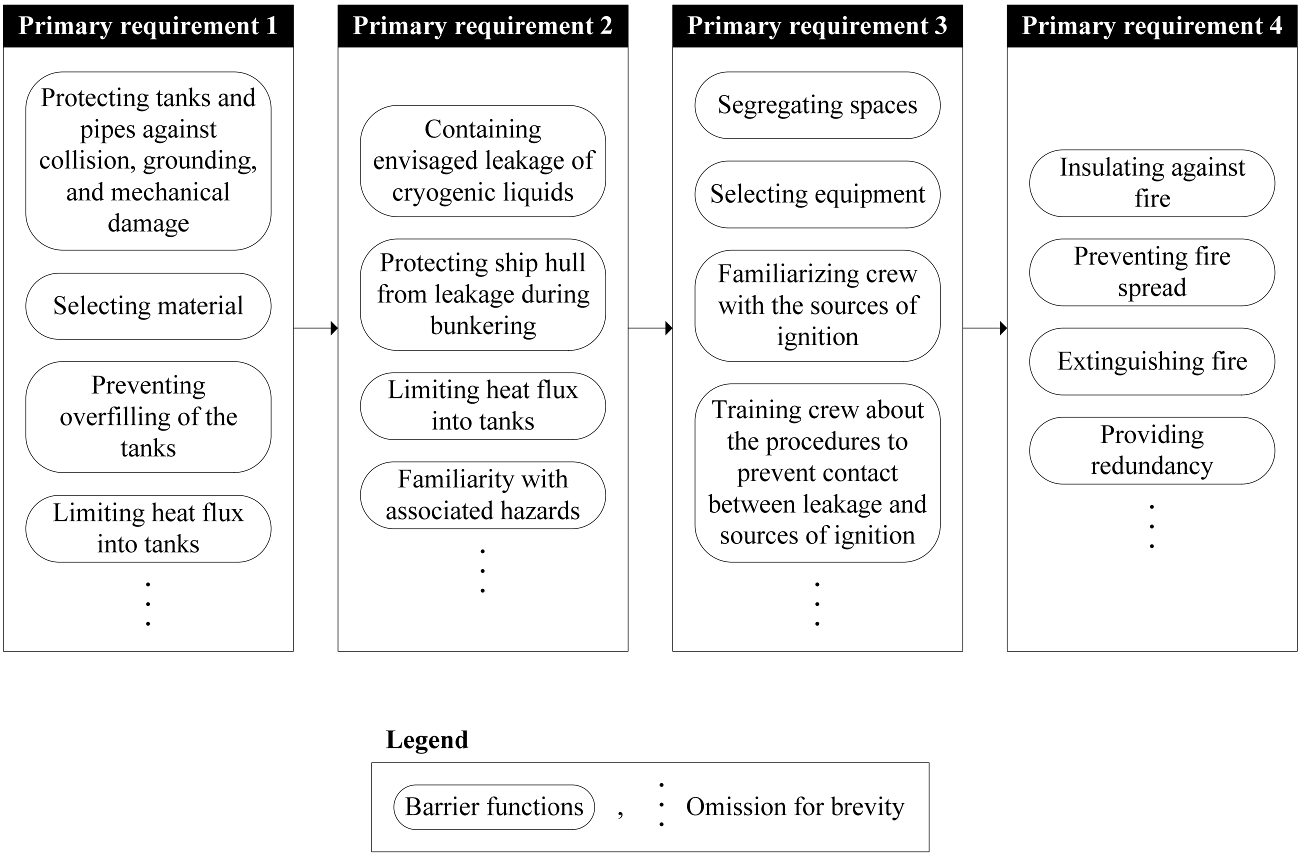

Figure 4: Reduced functional behaviour based on IMO (2015b, 2015d); SIGTTO (2000, 2002, 2011). Table 1 defines the primary requirements.

A bowtie diagram complements the functional behaviour model by showing that the fulfilment of the single safety requirements may prevent an accident on several levels, which are not sequential, even though Figure 4 might indicate the opposite. A bowtie diagram is a graphical illustration of an accident scenario, starting from accident causes and ending with the consequences. While centred on a critical (or top) event, the composition of a bowtie diagram may be described as a Fault Tree on the left-hand side and an Event Tree on the right-hand side (Khakzad et al., 2012). The former identifies the possible events that could cause the critical event, whereas the latter shows the possible consequences of the critical event. Safety barriers[8] may be employed on both sides

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[8] Safety barriers are technical, operational, and organizational means to reduce the possibility for occurrence of an error/hazard/accident or limit its consequences (PSA, 2013). Systems engineers can identify the safety barriers necessary to ensure safety and effectively communicate them to ship owners, designers, and crew who, in turn, must enforce them.

to stop the development of the accident scenario. As shown in Figure 5, barrier functions and, in turn, barrier elements are enforced by the primary requirements previously defined in Table 1.

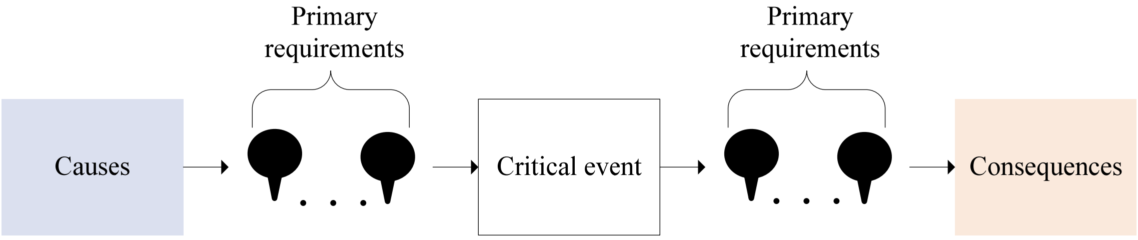

Figure 5: Bowtie diagram

Figure 6 shows representative results from a bowtie analysis performed on a LNG carrier, considering leakage as the critical event. This bowtie diagram was obtained by applying a common bowtie analysis technique (i.e., Methodology for the Identification of Major Accident Hazards (Delvosalle et al., 2006)). Such analysis is qualitative. In order to perform quantitative modelling (as addressed in CPR (2005)), detailed data on the arrangement of the fishing vessel are needed. The number tags on the diagram indicate where some representative barrier functions are located, i.e., where the action of some primary requirements shown in Table 1 may stop the unwanted events. However, the number tags show only certain barrier functions. More specifically, only the barrier functions included in Figure 4 are illustrated in Figure 6. After deriving a complete functional behaviour model, barrier functions and their corresponding number tags can be assigned to other branches of the bowtie diagram.

The bowtie analysis in Figure 6 clarifies the scope of the primary requirements and their barrier functions. In addition, the bowtie analysis provides an overview of potential accident scenarios to be prevented and raises awareness about the potential consequences if the safety MOE is not fulfilled. For instance, Primary requirement 1, among other things, has functions that prevent the critical overpressure of a LNG tank. If these functions fail, the tank pressure can potentially raise until leakage (i.e., a critical event) occurs. At this point, some Primary requirement 2 functions can contain the leakage and avoid the formation and evaporation of pools. Failure of this function exposes the leaked LNG/natural gas to ignition – instant ignition may also occur, but the risk of exposure to possible ignition sources increases as the LNG spreads further. The goal of Primary requirement 3 functions is the prevention of ignition, and a serious catastrophic event, such as a vapour cloud explosion may occur if they fail (Vílchez et al., 2011). The goal of Primary requirement 4 functions is to minimize the consequences of such an accident. Failure of these functions may lead to a domino effect and extensive damage. Figure 6 does not consider whether sufficient barriers are in place for the critical event, but it can be used as an input for such an analysis.

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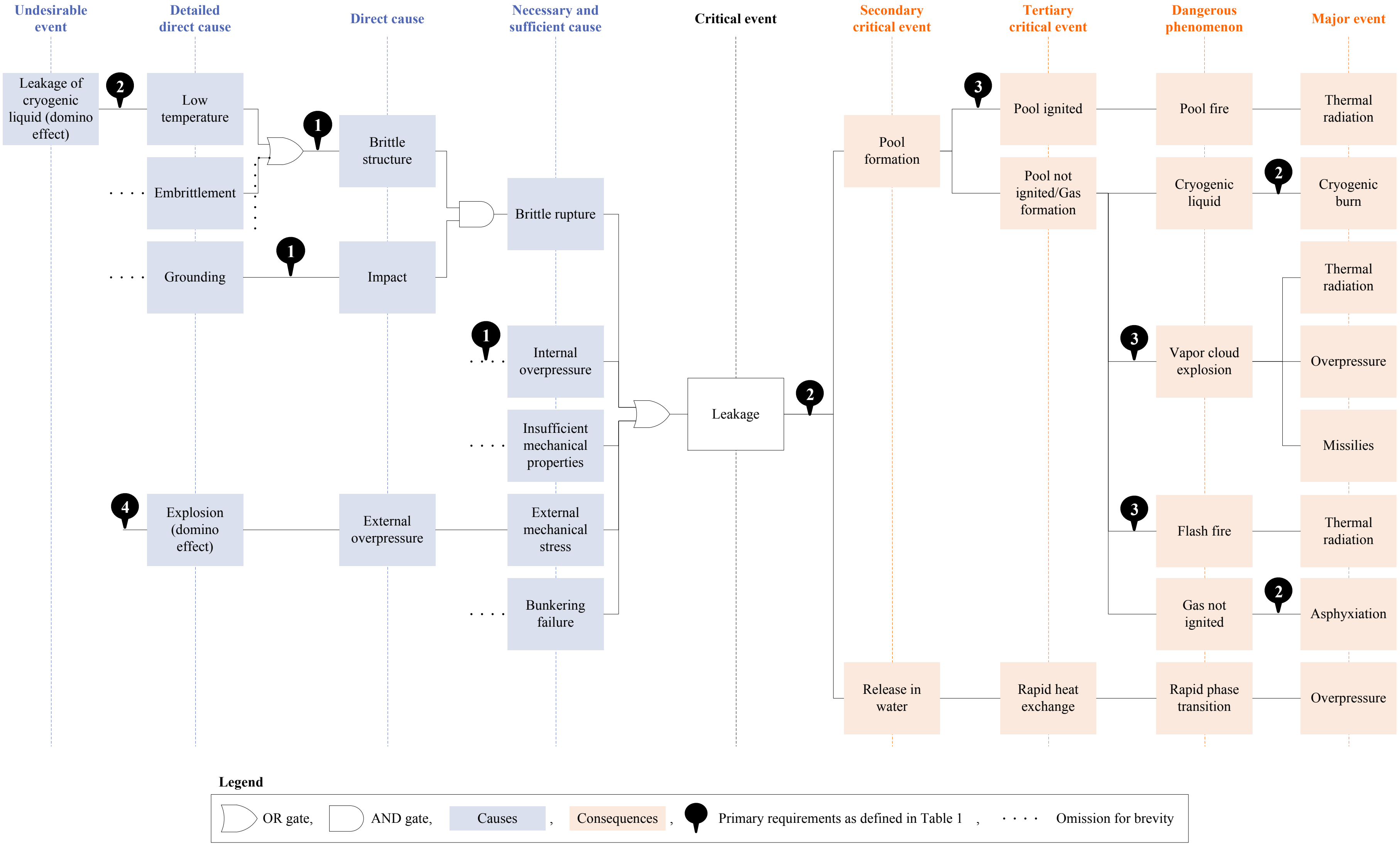

Figure 6: Bowtie diagram concerning the leakage of a LNG tank on a carrier ship adapted from Paltrinieri et al. (2015)

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4.4.3 Architecture

Figure 7 shows the reduced architecture model. In this study, the main component is the overall system, which is composed of technical and operational safeguards (i.e., barrier elements) on a LNG-fuelled fishing vessel. This diagram provides an overview of the barrier elements that are included in the system to ensure safety.

In the case under study, different barrier elements can fulfil the safety requirements of the system. For instance, one of the requirements under Primary requirement 1 is to “Control cargo boil-off”. This requirement involves controlling boil-off and overpressure, which could damage the tank. Various barrier functions work together to fulfil this requirement, such as the “Limiting heat flux into tanks” function. Such heat flux may occur during normal operations or unwanted events, such as a fire on the ship. One of the barrier elements that can limit the heat flux is proper “Thermal insulation of tanks […]”. Designers have different options for thermal insulation, such as polyurethane and mineral wool (SIGTTO, 2011). The same holds for the other requirements, functions, and barrier elements. For instance, different training plans may be considered. Different final safety systems may be established based on the choices made by the designer, and thus, various alternatives may be considered for a LNG-fuelled ship.

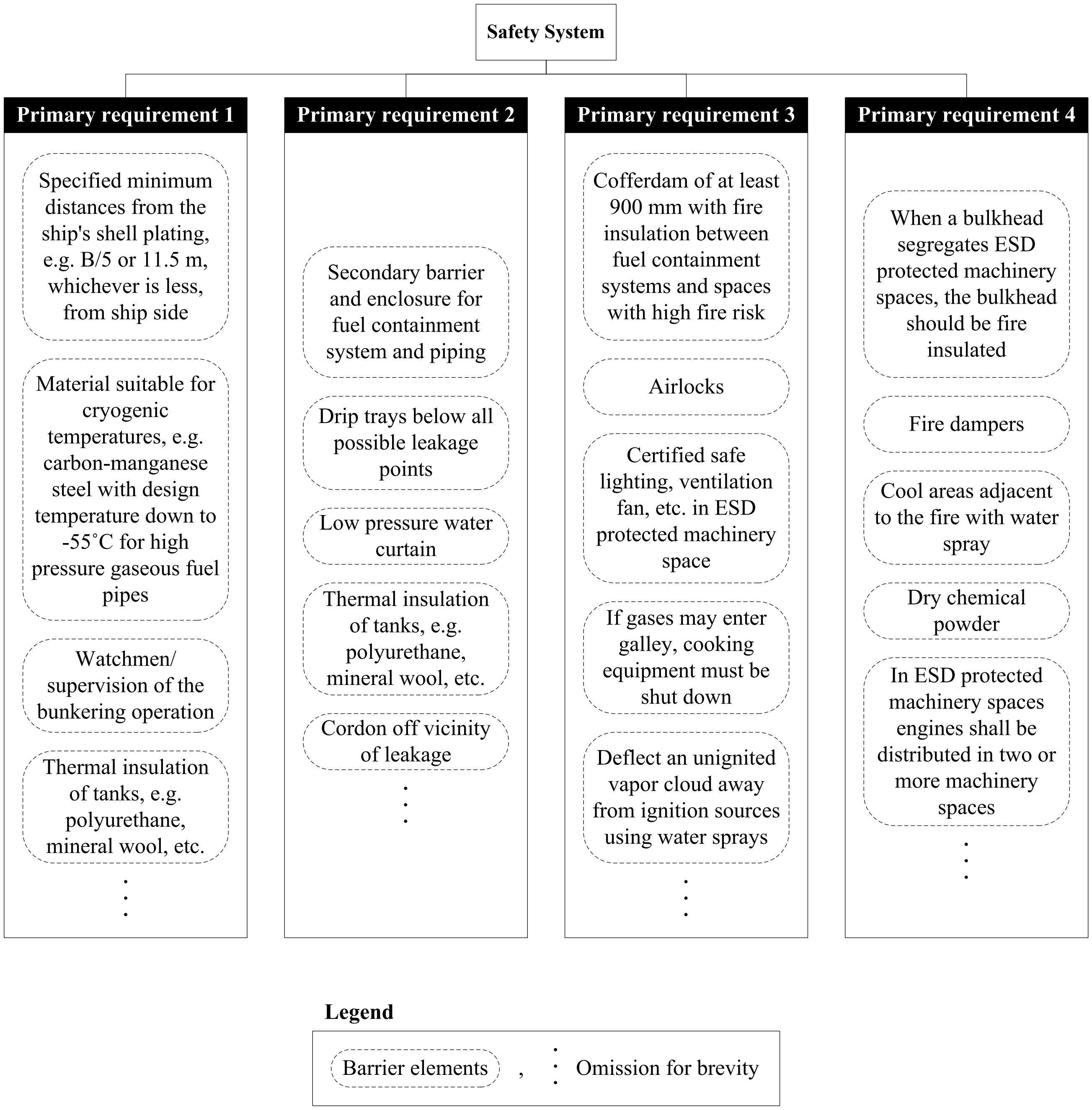

Figure 7: Reduced architecture based on IMO (2015b, 2015d); SIGTTO (2000, 2002, 2011). Table 1 defines the primary requirements.

4.5 Step 5 - Trade-off analysis

Two MOEs were defined in Section 4.3: (i) compliance with safety requirements and (ii) the LCC. The trade-off analysis uses these MOEs as criteria to evaluate and compare alternative designs for an LNG-fuelled vessel. If no feasible solution was found, iteration back to Step 2 is performed (see Section 3) to gather additional information that may lead to new alternatives that were not initially considered. The MOEs may also be revisited to improve decision-making.

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Different alternatives are possible. For example, one alternative is to elongate the vessel to accommodate the gas unit. Another alternative is to reduce the size of the fish hold to create space for the gas unit. These alternatives and other possible options should be evaluated and compared with respect to the MOEs. For illustration, the remainder of this sub-Section evaluates the LCC of the former alternative by means of the net present value (NPV) technique. We assume compliance with safety requirements because their evaluation is out of the scope of this study.

To evaluate the feasibility of the investment in LNG, it is compared with the baseline MGO investment. We are mainly interested in the additional/fewer capital and operational costs associated with powering the vessel with 100% LNG rather than MGO. Other lifecycle stages are not considered. The following costs have been considered:

- Difference between the cost of a conventional diesel engine and a gas engine,
- Cost of the LNG tank,
- Cost of elongating and modifying the ship hull to fit in the LNG tank while keeping the fish hold capacity intact,
- Support from the NO_x fund,
- Difference between the MGO and LNG fuel costs, and
- Difference between the environmental taxes.

4.5.1 Vessel characteristics

A coastal shrimp trawler operating in Norway was selected as the vessel for consideration. It was assumed that a new vessel with the characteristics shown in Table 2 was built in 2016. A 25-year lifetime of the vessel was assumed.

This vessel was chosen for the following primary reasons:

- Because the vessel operates within 250 nm of shore and its engine power is greater than 750 kW, it is liable to NO_x, SO_x, and CO_2 taxes (see Section 4.2.3). Therefore, LNG fuel can reduce these costs.
- Considering a MGO density of 0.86 kg/L (NP, 2013) and the fuel consumption and catch data in Table 2, the fuel use coefficient[9] of the vessel was approximately 2.13 kg fuel/kg fish in 2012. This amount is considerably higher than the corresponding value for the Norwegian fishing fleet without a shrimp catch (i.e., below 0.3 kg fuel/kg fish) (Jafarzadeh et al., 2016). Therefore, this vessel consumes relatively large amounts of fuel to catch fish. The vessel may save on fuel costs by using LNG.

Table 2: Characteristics of a coastal demersal trawler operating in Norway. The values are derived from Directorate of Fisheries (2014), except for depth, which is assumed.

Characteristic	**Value**
Length overall (m)	33.18
Breadth (m)	7.20
Depth (m)	5.96
Gross tonnage	279

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[9] In fisheries, a fuel use coefficient (kg fuel/kg fish) can indicate the energy efficiency. High fuel use coefficients indicate low energy efficiency and vice versa (Jafarzadeh et al., 2016).

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Main engine power (kW)	760
Days at sea in 2012	280
MGO consumption in 2012 (L)	407,030
Catch in 2012 (kg)	164,454

4.5.2 Engine

For operation on MGO, an engine with 760 kW that complies with Tier II of MARPOL Annex VI regulations on NO_x emissions (see IMO (2014a)) was chosen. This engine cost approximately 1.85 MNOK (0.21 MUSD)[10] in 2016 (Engine suppliers, 2016).

An 845 kW engine was chosen based on the gas engines available in the market. The engine is approved for marine applications. The gas engine cost approximately 3.75 MNOK (0.43 MUSD) in 2016 (Engine suppliers, 2016). This price covered the engine, its control and monitoring system, and the gas valve unit. Therefore, the gas engine was approximately 100% more expensive than the conventional engine. The price difference is **1.90 MNOK (0.22 MUSD).**

4.5.3 LNG tank

The following steps were performed to estimate the LNG tank cost:

- First, the fuel consumption for a round trip was estimated.
- Second, the LNG tank volume was estimated.
- Finally, the cost was estimated based on the tank volume.

Fuel consumption for a round trip

Fiskeriportalen (2016) provided an overview of the dates that Norwegian fishers land their catch. The length of each voyage in 2015 has been estimated assuming that the vessel has been operating between two consecutive landing dates. Six days is the average round-trip length.

Using the days at sea and the fuel consumption data in Table 2, the average MGO consumption for a round trip was calculated as **8.72 m^3** of MGO. The energy consumed during a round-trip can be estimated using Equation (1) together with MGO and the diesel engine characteristics shown in Table 3:

$$E_r\ (kWh) = \frac{FC_r(m^3) \times \rho(\frac{g}{m^3})}{sfc(\frac{g}{kWh})} \tag{1}$$

where *E*, *FC*, *ρ*, and *sfc* are the energy consumption, fuel consumption, density, and specific fuel consumption of the engine, respectively. The subscript *r* indicates a round-trip. The energy necessary for a round-trip is **35.17 MWh**.

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[10] MNOK and MUSD respectively stand for million NOK and million USD.

If the vessel consumes 100% LNG instead of MGO, the LNG required for a round trip can be estimated using Equation (1) and the LNG and gas engine characteristics (Table 3). The LNG consumption for a round trip is approximately **15.55 m^3.**

The approach taken for estimating fuel consumption was simplified due to lack of data on the operational profile of the vessel. In cases where detailed data is available, modelling and simulation of power system of vessels under different operational profiles may reduce inaccuracies (Baldi et al., 2015; Figari and Soares, 2009; Jafarzadeh et al., 2014; Martelli et al., 2013; Martelli et al., 2014).

Table 3: Characteristics of LNG and MGO fuels and their corresponding engines

Parameters	**Amount**	**Source**
Round trip (days)	6	This study
Gas engine power (kW)	845	(Engine suppliers, 2016)
Average sfc of gas engine [a,b] (g/kWh)	198.99	(Engine suppliers, 2016)
LNG density (g/m^3)	45×10^4	(IGU, 2012)
Energy content of LNG (MWh/tonne)	13.80	(Skjervheim, 2012)
Marine diesel engine (kW)	760	(Directorate of Fisheries, 2014)
Average sfc of conventional engine [a] (g/kWh)	213.30	(Engine suppliers, 2016)
MGO density (g/m^3)	86×10^4	(NP, 2013)
Energy content of MGO (MWh/tonne)	11.90	(Skjervheim, 2012)

[a] The gas engine is more energy efficient than the diesel engine at higher powers. However, the opposite is true for lower powers. The average specific fuel consumption (sfc) in the entire power range has been considered due to a lack of data on the operational profile of the vessel.

[b] The engine supplier provided the fuel rate in the gaseous state (Nm^3/h). "N" refers to the normal state (0˚C, 1 atm). We assumed 1 tonne LNG equivalent for 1,300 Nm^3 gas (IGU, 2012) while converting fuel rates to sfc (g LNG/kWh).

LNG tank volume

Depending on the relief valve setting, the usable capacity of LNG is approximately 80–85% of the tank volume (Boulougouris and Chrysinas, 2015). Considering a round-trip LNG consumption of 15.55 m^3 and a usable capacity of 85% (Jetlund, 2016), the gross volume of LNG tank is approximately **18.30 m^3**.

LNG tank dimensions

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The next step was to estimate diameter and length of the tank. The IGF Code states that “the fuel tanks shall be located at a minimum distance of B/5 or 11.5 m, whichever is less, measured inboard from the ship side at right angles to the centerline at the level of the summer load line draught” (IMO, 2015b). In addition, “the lowermost boundary of the fuel tank(s) shall be located above the minimum distance of B/15 or 2.0 m, whichever is less, measured from the moulded line of the bottom shell plating at the centerline” (IMO, 2015b).

A simplified case was considered and is shown in Figure 8. It is assumed that the breadth in Table 2 represented the moulded breadth. Because trawlers use the vessel’s deck for fishing operations, the tank was positioned below deck. Considering the vessel’s breadth and depth (Table 2), the maximum breadth of the tank with insulation could be **4.32 m** (i.e., vessel breadth minus B/5 from each side of the ship), whereas the maximum depth of the tank with insulation could be **5.48 m** (i.e., vessel depth minus B/15). Because the tank is cylindrical, a diameter of **4.32 m** with insulation was chosen.

The insulation of tanks typically has a minimum thickness of 25 cm (Jetlund, 2016). We assumed a 30 cm thickness for the insulation and the inner and outer steel walls (Wold, 2016). Therefore, the tank diameter without the insulation and walls is **3.72 m**. Considering the LNG tank size (i.e., 18.30 m^3) and diameter (i.e., 3.72 m), the tank is approximately **1.68 m** long.

The pressure build-up unit, LNG vaporizer, tank connections, and tank valves are included in a gastight space welded to the outer tank, termed a cold box (ECE, 2014). The size of the cold box varies with the valve and vaporization installations. It is typically installed at the extension of the tank with an additional length of, for example, 1.5–3 m (Jetlund, 2016). In this study, a cylindrical extension of 1.5 m was assumed. Therefore, the length of the tank, including the cold box, was increased to **3.18 m**. Table 4 summarizes the LNG tank dimensions.

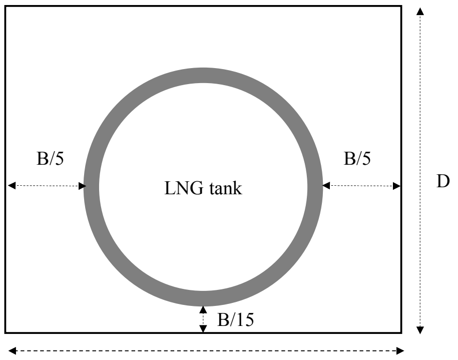

Figure 8: Section view of the LNG tank within the vessel. B and D denote the breadth and depth of the vessel, respectively. The shaded area represents the insulation and walls.

Table 4: LNG tank dimensions

Item	**Amount**
Usable capacity of the LNG tank (%) (Boulougouris and Chrysinas, 2015; Jetlund, 2016)	85
LNG tank diameter without insulation and tank walls (m)	3.72
Insulation and inner and outer wall thicknesses (cm) (Jetlund, 2016; Wold, 2016)	30

LNG tank length (m)	1.68
LNG tank length including the cold box (m)	3.18
Gross tank volume [a] (m^3)	18.30
Insulated LNG tank volume [b] (m^3)	24.67

[a] 85% usable capacity of LNG was considered. This value excludes the insulation, walls, and cold box.

[b] Excluding the cold box

LNG tank cost

In 2016, the cost of an LNG tank ranged from approximately 40 kNOK/m^3 (4.62 kUSD/m^3)[11] gross volume for larger tanks (e.g., 1,000 m^3) to 150 kNOK/m^3 (17.34 kUSD/m^3) gross volume for smaller tanks (e.g., 20 m^3). These costs included expenses related to the tank manufacturing (e.g., the cold box, bunker stations, bunker pipes, gas pipes, and electrical interface). However, they do not include expenses for the tank control system, the ventilation system, and other shipyard-related expenses. The cost of the LNG tank for this study was approximately **2.74 MNOK (0.32 MUSD)** (Jetlund, 2016). We assumed an additional **1.21 MNOK (0.14 MUSD)** for the gas control system, ventilation, gas detectors and shipyard installation costs (Stenersen, 2015). Therefore, the total cost was approximately **3.95 MNOK (0.46 MUSD)**.

4.5.4 Hull modification

The vessel can be elongated to fit the tank to the vessel without reducing the catch capacity. Due to lack of data on general arrangement of the vessel, an elongation cost of 1 MNOK/m (0.12 MUSD/m) was assumed (Einang, 2016). Considering a tank length of 3.18 m (Table 4), the hull modification cost was estimated to be **3.18 MNOK (0.37 MUSD)**.

4.5.5 Fuel cost

The vessel in this study operates in the North Sea, which is a sulphur ECA. Since 2015, the vessels operating in Sulphur Emission Control Areas (SECAs) are required to use fuel with a maximum sulphur content of 0.1% (IMO, 2014b), such as low-sulphur MGO (LSMGO) or LNG.

We considered the average LSMGO prices in Bergen, Norway from January to April 2016 as the cost basis, which is 361.50 USD/tonne (Ship & Bunker, 2016). Considering its energy content (Table 3) and exchange rate in the period of interest (1 USD ≈ 8.65 NOK) (Norges Bank, 2016) the price of LSMGO was 259.72 NOK/MWh (30.03 USD/MWh).

Among other things, the LNG price depends on the bunkering type and the distance from the LNG source. For the same energy content, we assumed a 10% lower price for LNG delivered on-board a vessel along the Norwegian coast compared to LSMGO (Einang, 2016; Marhaug, 2016)

Considering the annual MGO consumption (Table 2), the energy content and density of MGO (Table 3), and the difference in fuel prices, the annual fuel cost savings from the use of LNG instead of LSMGO was approximately **108.19 kNOK (12.51 kUSD)**. For simplicity, it is also assumed that the fuel costs remained the same during the vessel's lifetime.

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[11] Where kNOK and kUSD respectively stand for thousand NOK and thousand USD

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4.5.6 Environmental expenses and support

In this study, the environmental tax rates were assumed to be constant during the vessel's lifetime. The NO_x emissions for a MGO-fuelled vessel were calculated considering the annual MGO consumption (Table 2), the MGO density (Table 3), and an emission factor of 54 kg NO_x per tonne MGO (Stenersen, 2015). Considering a NO_x tax rate of 21.17 NOK (2.45 USD) per kg NO_x (see Section 4.2.3), the annual NO_x tax was **400.17 kNOK (46.26 kUSD)**.

It is assumed that the use of 100% LNG would reduce NO_x emissions by 90%. The vessel can pay 4 NOK (0.46 USD) per kg NO_x to the NO_x fund instead of the tax for the remaining emissions (see Section 4.2.3). By using LNG, the annual savings on the NO_x tax will be **392.60 kNOK (45.39 kUSD)**.

The vessel can also receive 375 NOK (43.35 USD) per kg NO_x reduced as support from the NO_x fund. However, the support may not exceed 80% of the additional investment costs (see Section 4.2.3): (i) the additional cost of the gas engine compared to a conventional engine (1.90 MNOK (0.22 MUSD)), (ii) the LNG tank cost (3.95 MNOK (0.46 MUSD)), and (iii) the hull modification cost (3.18 MNOK (0.37 MUSD)). Therefore, **6.38 MNOK** (0.74 MUSD) of the additional investment cost (i.e., **9.04 MNOK (1.05 MUSD)**) can be covered by the fund.

Because the vessel in this study operates in coastal waters, it is subject to a tax on CO_2 and SO_x emissions when using MGO (i.e., 0.28 and 0.133 NOK (0.03 and 0.02 USD) per litre of MGO, respectively). Considering the annual MGO consumption (Table 2), the annual CO_2 and SO_x taxes were **113.97** and **54.13 kNOK (13.18** and **6.26 kUSD)**, respectively. LNG-powered fishing vessels are exempt from these taxes (Norwegian Directorate of Taxes, 2016).

4.5.7 Net present value

In previous sub-Sections, we estimated the relative costs for a LNG investment compared to a MGO investment. For many investments, such as the case under study, the main costs are incurred upfront and other costs and benefits are incurred in the future. The value of money changes over a vessel's lifetime. The NPV technique can be used to evaluate the LCC of an investment considering the time value of money (Pohl and Nachtmann, 2010).

Inflation and uncertainty, among other things, cause future costs and benefits to be discounted to express their current value. The discount rate i depends on various factors, such as the interest rate paid by the government on treasury bonds and the prime rate charged by major banks to their best customers. Once all of the costs and benefits are determined, the present value of the costs is subtracted from the present value of the benefits to determine the NPV (Equation (2)) (Fields, 2009).

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{2}$$

where B_t and C_t represent the additional/fewer benefits and costs of a LNG-fuel investment at time t compared to a conventional vessel, respectively, and n represents the years covered. For an investment with a positive NPV, the present value of the benefits exceeds the present value of the costs, and the investment is deemed feasible.

Figure 9 summarises the various additional capital and operational costs and benefits for the LNG investment compared to the conventional MGO investment. The capital costs include the additional engine cost, the expenses related to the LNG tank, and the hull modification cost. All of these costs are incurred when the vessel is built (i.e., *t*=0). The operational costs of a LNG-fuelled vessel are less than the corresponding values for a conventional vessel. Therefore, the LNG-fuelled vessel has operational benefits/savings on fuel costs and environmental taxes compared to the conventional vessel. The NO_x fund support is received in stages. For instance, NO_x reduction after a month will elicit possible partial support. The payment will be adjusted according to each emission reported toward full payment in relation to NO_x reduction achieved after 3–12 months of operation. The verification period is generally one year, and a part of the total verified support can be received every 2–3 months (Fleddum, 2016; NHO, 2016a). In the case under study, it is assumed that all of the support was received after the first year (i.e., *t*=1).

The calculation of the discount rate is outside the scope of this study. Here, we assume a discount rate *i* of 8%. We assume that *n* equals the vessel's lifetime (i.e., 25 years). For the case under study, Equation (2) can be expressed as Equation (3):

$$NPV = -(1.90 + 3.95 + 3.18) + 6.38\left[\frac{1}{(1+0.08)^1}\right] + (0.11 + 0.39 + 0.11 + 0.05)\left[\frac{(1+0.08)^{25}-1}{0.08(1+0.08)^{25}}\right] = 4.01\ MNOK \tag{3}$$

If the ship owner invests in a LNG-fuelled vessel instead of a conventional vessel, with an 8% discount rate, 4.01 MNOK (0.46 MUSD) in 25 years accrues. In other words, the LNG investment is economically more beneficial than a conventional investment. The payback time is 7 years.

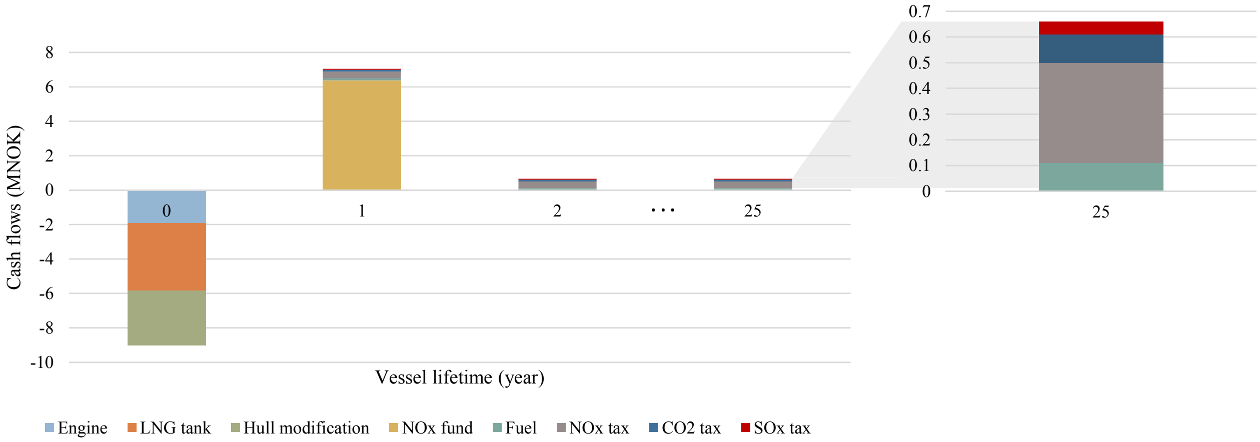

Figure 9: Cashflow for a LNG investment compared to a MGO investment during the vessel's lifetime

4.6 Step 6 - Build and test the plan

When a feasible design has been established, an implementation plan is produced. The plan accounts for the available resources for implementation, the technical risk, and subcontracting, among other details (Oliver et al., 1997). Producing the implementation plan is outside the scope of this study and is thus not further discussed.

5 Discussion

5.1 Knowledge transfer

LNG does not resemble any fuel that fishermen have experience with from either an economic perspective or a safety perspective. Still, LNG may be a viable alternative for meeting environmental regulations. LNG can reduce fuel costs in this fuel-intensive sector; however, other costs should also be considered while evaluating economic feasibility of a LNG investment. In addition, the present safety concerns in fishing increase the complexity of this issue. This article uses a SE approach to increase the knowledge of ship owners and other stakeholders regarding the financial, technical, and operational aspects of using LNG fuel.

Progressively tightening environmental regulations increase the complexity of investment decisions. Ship owners can use a holistic approach to harness the environmental benefits of LNG with a better understanding of its economic and safety implications. The SE approach can assist ship owners in decision-making and trade-off analyses. The most appropriate design for meeting environmental requirements can be selected based on defined criteria, such as the MOEs defined in Section 4.3.

Naval architects can use the SE approach to manage and organize the relevant information and regulations, such as the IGF Code, while designing a LNG-fuelled system. This approach aids in the understanding of the rationale behind the rules and may thus enhance ship design. The SE process stresses the importance of the early definition of system requirements and stakeholder criteria. In this manner, it prevents fundamental requirements from being overlooked during the downstream system design. In addition, the SE approach covers different stages of the life cycle, which allows the effects of the design on the operation to be identified early in the design process. For instance, possible interactions between the gas unit or bunkering system and the fishing operation can be identified well in advance. In the same manner, gas-related safety training can be planned with fishing operations in mind.

The link between the SE approach and the bowties shows where the action of different safety barriers can prevent undesirable events in different accident scenarios and illustrates the consequences of not satisfying the MOEs. This allows for an assessment of the overall system safety based on the relative importance of primary requirements and also helps the ship owners, designers, and crew prioritize their actions to improve the overall safety of the system and prevent accidents.

SE can also be useful operationally. Using the SE process, ship owners can realize which skills are needed for safe operations and plan crew training accordingly. Training can extend beyond educating the crew about hazards and proactive and reactive safety operations; it can also inform the crew about the reasons behind the required steps. If the crew realizes the logic behind their safety actions, they are more likely to comply with the procedures that they are expected to follow. As noted above, the crew training requirements on a LNG-fuelled ship (i.e., Section A-V/3 in the STCW Code) demand some knowledge of the technical requirements of these vessels (i.e., the IGF Code). The SE approach may facilitate the understanding of these technical requirements and their link to the operational requirements.

5.2 LCC analysis revisited

Several assumptions were made while estimating the LCC of the LNG investment in Section 4.5. For example, the fuel price was assumed to be constant during the vessel's lifetime. However, the actual future prices of MGO and LNG are highly uncertain. Different fuel price projections should be considered to reduce the investment risk.

While fuel projection is outside the scope of this study, the LNG investment was revisited considering two scenarios from DNV GL and MAN Diesel & Turbo (2015). These scenarios are shown in Figure 10. The first scenario is a high-price scenario based on mid-2014 fuel prices (Scenario I). The second scenario is a low-price scenario based on mid-2015 prices (Scenario II). In these scenarios, LNG is on average 41% and 24% less expensive than MGO for the same energy content, respectively. We assumed that MGO and LNG prices would

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increase at the same rate during the vessel's lifetime (i.e., from 2016 to 2041). Keeping the remaining parameters and costs unchanged (see Section 4.5), the NPV will rise to the values shown in Table 5. Therefore, the analysis is highly sensitive to fuel price dynamics, which should be considered.

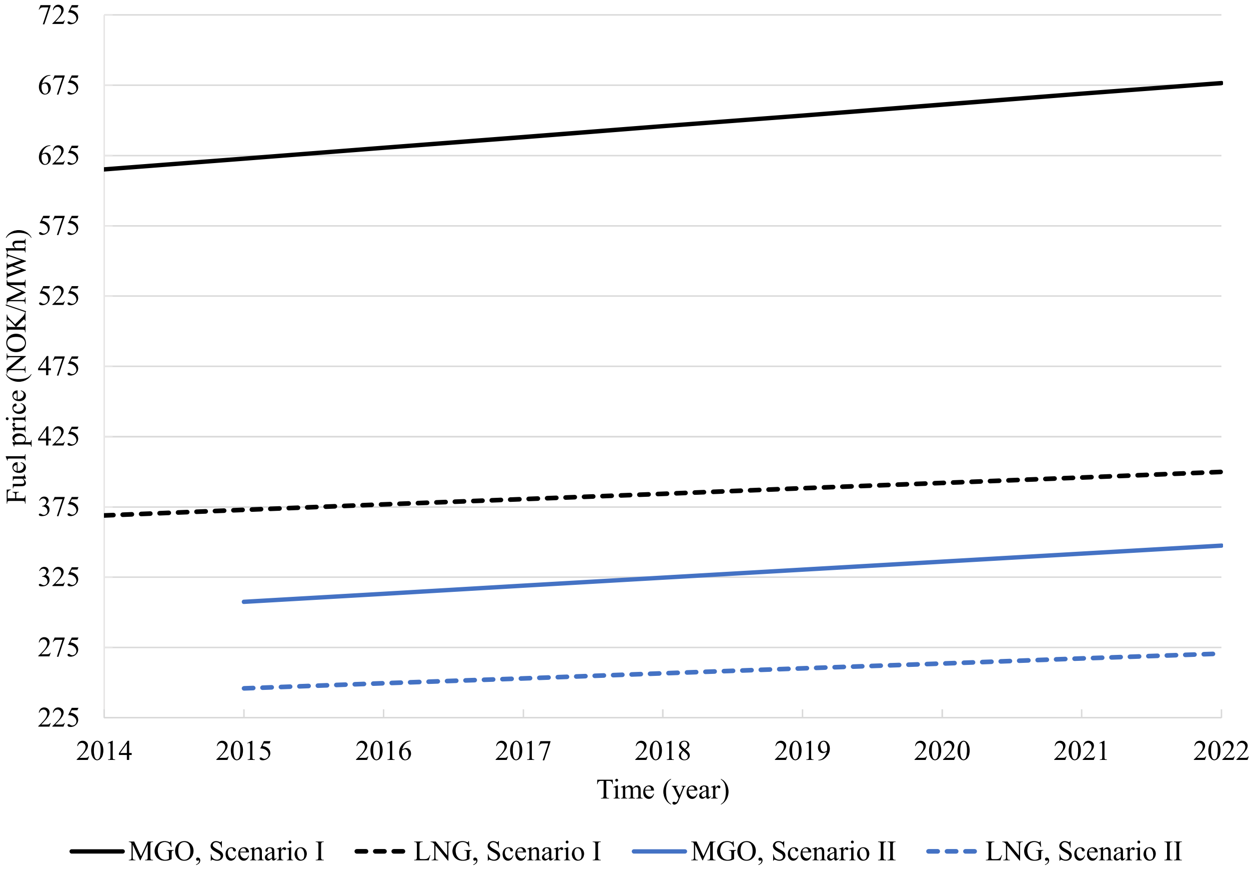

Figure 10: Two fuel price scenarios based on DNV GL and MAN Diesel & Turbo (2015). Exchange rate of 8.65 NOK/USD is used to convert values.

Table 5: Relative net present value (NPV) of the LNG investment compared to the MGO investment. The LNG investment is feasible in scenarios with positive NPV and vice versa. Case study in Section 4.5 is the base case. Scenario I and II consider high and low price projections defined by DNV GL and MAN Diesel & Turbo (2015), respectively. Scenario III considers no tax and support for emissions of nitrogen oxides.

Scenario	**NPV in MNOK (MUSD)**
Base case	4.01 (0.46)
Scenario I	15.76 (1.82)
Scenario II	6.60 (0.76)
Scenario III	-6.09 (-0.70)

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Different scenarios for environmental tax projections may be considered in a similar manner. For instance, although LNG only reduces CO_2 emissions by approximately 25%, LNG-fuelled vessels are exempt from the CO_2 tax in Norway. For the case under study and considering the current low fuel prices, the annual economic gain from the CO_2 tax exemption is close to the annual fuel cost savings when using LNG (see Sections 4.5.5 and 4.5.6). A possible future CO_2 tax could make LNG a less desirable solution, especially if fuel prices are low.

Table 5 indicates that LNG would not be a viable option when excluding the NO_x tax and fund system (Scenario III) while keeping the other parameters and costs unchanged (see Section 4.5). In addition, the vessel under study operated in the North Sea, which is a SECA. Vessels operating in SECAs are obliged to use a low-sulphur fuel (e.g., LSMGO or LNG) or use scrubbers to clean the exhaust gas. LNG may be less desirable for a vessel that spends less time in SECAs because the vessel can use a less expensive fuel (e.g., heavy fuel oil) outside of the SECAs. Therefore, the viability of LNG may change from one region to another based on environmental regulations, taxes, and supports.

The effects of crew training and hiring on costs were not considered due to the lack of specific data. These costs may add to the expenses of the LNG investment. Maintenance costs were also not considered. Gas engines may require less frequent maintenance; however, the spare parts may be more expensive (see Section 2.2).

In this study, NPV was used for the LCC analysis. Although this technique is simple to use and provides a good overview of costs, it has drawbacks. For instance, NPV cannot evaluate the value of investing in a technology at a later stage. Acciaro (2014) suggests other methods, such as a real option analysis (ROA), for this purpose.

In this study, the LNG tank was assumed to be horizontal. However, vertical tanks are another option. In this manner, the tank may be positioned in available free spaces on the vessel. However, this option was not evaluated due to the lack of data on the ship arrangement.

In this study, the tank volume including insulation was 24.67 m^3 (Table 4), which is approximately 2.8-fold larger than the MGO tank volume (i.e., 8.72 m^3) (see Section 4.5.3). Bagniewski (2010) reported a corresponding value of 2.3 fold for the maximum filling ratio of 95% (see Section 2.2). However, it is not clear whether the minimum filling ratio of 10% was considered (i.e., a net 85% usable capacity). The thicknesses of the insulation and the inner and outer walls were also unknown. More importantly, we used Equation (1) to estimate the fuel consumption for a round trip. In other words, we investigated the actual energy needed by considering the average efficiency of diesel and gas engines. If we had instead considered the energy content of MGO and LNG as shown in Table 3, the LNG consumption for a round trip would have been 14.37 m^3 (as opposed to the current value of 15.55 m^3). Assuming this value and a usable capacity of 95% (instead of the 85% value used), the LNG tank would be 2.3-fold larger than the MGO tank.

5.3 Limitations

Despite its benefits, the SE approach has some limitations. It may be challenging to define MOEs. Different stakeholders should agree on these measures well in advance to avoid costly problems in the future. Although models enable the investigation of systems from different perspectives, the construction of accurate models is time and resource consuming. Professionals from different disciplines, such as naval architects, safety engineers, and equipment suppliers, should collaborate to collect and analyse the data. In addition, some stakeholders may be familiar with compiling and analysing data in a text and document format. It may be difficult to define the relationship between requirements, barrier functions, and barrier elements, as different pieces of information are spread across different documents. Finally, cost estimation for relatively new technologies, such as LNG propulsion, may be challenging. There are few gas engine and equipment suppliers, which causes cost data to be confidential and less accessible. The LNG price is highly uncertain and varies from one region to another. There is also room for negotiation on fuel price, both for MGO and LNG, for major fuel consumers.

6 Conclusions

This article illustrates how a SE approach can increase the knowledge of ship owners, naval architects, and the crew regarding the financial, technical, and operational aspects of the use of LNG fuel. Fishing vessels can use LNG fuel to improve their environmental profile. The vessels can comply with progressively tightening environmental regulations in this manner while satisfying customers who want "green" seafood products. Better insight into LNG economic and safety aspects may support ship owners when evaluating such available options. Moreover, naval architects may benefit from better management of the available information and the crew may improve their understanding of the safety rationale. In fact, combining a SE and bowtie analysis allows for the visualization of the potential effects when missing safety requirements.

This representative application demonstrates how an organised approach such as SE can enhance decision-making on risk prevention, the selection of feasible alternatives, and harmonisation between the system elements and environment. Specifically, this case study demonstrates that LNG may be cost efficient for coastal shrimp trawlers, but the results depend on fuel prices and environmental taxes and supports. The results may be applicable to other parts of the fishing fleet, particularly those parts of the fleet that have high fuel consumption.

The suggested approach may be broadened and applied to other ship types. Additional stakeholder requirements may be added to the SE models. The economic feasibility of alternative LNG-fuelled designs, such as the use of dual fuels (i.e., MGO and LNG) or the use of smaller fish holds for accommodating LNG tanks, may also be of interest.

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8 References

Acciaro, M., 2014. Real option analysis for environmental compliance: LNG and emission control areas. Transportation Research Part D: Transport and Environment 28, 41-50.

Altosole, M., Buglioni, G., Figari, M., 2014. Alternative Propulsion Technologies for Fishing Vessels: a Case Study. International Review of Mechanical Engineering (IREME) 8(2), 296-301.

Avadí, A., Fréon, P., 2013. Life cycle assessment of fisheries: A review for fisheries scientists and managers. Fisheries Research 143, 21-38.

Bagniewski, M., 2010. LNG fuel for ships- a chance or a must? Det Norske Veritas (DNV), Gdynia, Poland.

Baldi, F., Johnson, H., Gabrielii, C., Andersson, K., 2015. Energy and exergy analysis of ship energy systems – the case study of a chemical tanker International Journal of Thermodynamics 18(2), 82-93.

Bazari, Z., Longva, T., 2011. Assessment of IMO mandated energy efficiency measures for international shipping. IMO, London, UK.

Bengtsson, S., Andersson, K., Fridell, E., 2011. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 225(2), 97-110.

Benvenuto, G., Laviola, M., Campora, U., 2013. Simulation model of a methane-fuelled four stroke marine engine for studies on low emission propulsion systems, Developments in Maritime Transportation and Exploitation of Sea Resources. CRC Press, pp. 591-597.

Boulougouris, E.K., Chrysinas, L.E., 2015. Lecture notes on LNG fueled vessels design training. University of Strathclyde, Glasgow, Scotland.

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. Journal of Cleaner Production 74, 86-95.

Buhaug, Ø., Corbett, J.J., Eyring, V., Endresen, Ø., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Wu, W., Winebrake, J.J., Yoshida, K., 2009. Second IMO GHG Study 2009. IMO, London, UK.

Chryssakis, C., Brinks, H., King, T., 2015. The fuel trilemma: Next generation of marine fuels. DNV GL, Oslo, Norway.

Cozzani, V., Rota, R., Tugnoli, A., Busini, V., Bubbico, R., Salzano, E., Uguccioni, G., 2011. Safety of LNG regasification terminals: The blue book approach. Chemical Engineering Transactions 24, 1105-1110.

CPR, 2005. The "Purple book"- Guideline for quantitative risk assessment, CPR 18E. Committee for the Prevention of Disasters (CPR), The Hague, Netherlands.

Dahl, H.J., 2001. Norwegian natural gas transportation systems: operations in a liberalized European gas market. Doctor of Engineering, Faculty of Engineering Science and Technology, Norwegian University of Science and Technology (NTNU).

Danish Maritime Authority, 2012. North European LNG infrastructure project- A feasibility study for an LNG filling station infrastructure and test of recommendations.

Danish Maritime Authority, 2015. Report of conclusions- 95th session of the IMO Maritime Safety Committee (MSC 95) 3 to 12 June 2015. Danish Maritime Authority, Valby, Denmark.

Davies, P.A., Fort, E., 2013. LNG as a marine fuel: Likelihood of LNG releases. Journal of Marine Engineering & Technology 12(3), 3-10.

Delvosalle, C., Fievez, C., Pipart, A., Debray, B., 2006. ARAMIS project: A comprehensive methodology for the identification of reference accident scenarios in process industries. Journal of Hazardous Materials 130(3), 200-219.

Directorate of Customs and Excise, 2015. Excise duty on emissions of NOx. Department, E., Oslo, Norway.

Directorate of Fisheries, 2014. Avtale om bruk av informasjon til forskning (Agreement on the use of information for research), In: Jafarzadeh, S. (Ed.), Norway.

DNV, 2008. Marpol 73/78 Annex VI- Regulations for the Prevention of Air Pollution from Ships. Det Norske Veritas (DNV), Norway.

DNV, 2011. Greener shipping in North America. Det Norske Veritas (DNV), Houston, USA.

DNV, 2012. Fish 2015- Pointing the way to the fishing industry of the future. DNV, Høvik, Norway.

DNV GL, 2014. LNG as ship fuel: The future- today. Hamburg, Germany.

DNV GL, 2015a. In focus- LNG as ship fuel- Latest developments and projects in the LNG industry. DNV GL-Maritime, Hamburg, Germany.

DNV GL, 2015b. Vurdering av tiltak og virkemidler for mer miljøvennlige drivstoff i skipsfartsnæringen. DNV GL, Høvik, Norway.

DNV GL, 2016. Ship list- Vessels in operation and vessels on order. Available: <https://www.dnvgl.com/maritime/download-confirmation/lng-vessels-in-operation.html> (accessed 12.04.2016).

DNV GL, MAN Diesel & Turbo, 2015. Cost and benefits of using alternative fuels, *6th Gas fuelled ship conference*. Motorship, Hamburg, Germany.

Driscoll, P.J., 2010. Systems Thinking, Decision Making in Systems Engineering and Management. John Wiley & Sons, Inc., pp. 25-64.

ECE, 2014. Proposed text of a derogation regarding the use of LNG for propulsion for a push boat to be built by Kooiman Marine. Economic Comission for Europe (ECE), Geneva, Switzerland.

EFTA, 2011. EFTA Surveillance Authority decision of 19 May 2011 on the notified scheme for the temporary NOx tax exemption for undertakings encompassed by an environmental agreement with the State on the implementation of measures to reduce emissions of NOx in accordance with a predetermined environmental target. European Free Trade Association (EFTA), Brussels, Belgium.

EIA, 2013. International energy outlook. Office of Integrated Analysis and Forecasting, Department of Energy, Energy Information Administration (EIA), forecasting, O.o.i.a.a., Washington DC, USA.

Einang, P.M., 2013. Gas fuelled ships- Norwegian experience, *Helios FP7 conference*. MAN Diesel & Turbo, Copenhagen, Denmark.

Einang, P.M., 2016. Personal communication, In: Jafarzadeh, S. (Ed.). MARINTEK, Norway.

Engine suppliers, 2016. Confidential personal communication, In: Jafarzadeh, S. (Ed.), Norway.

FAO, 2012. Report of the expert workshop on greenhouse gas emissions strategies and methods in seafood. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Fet, A.M., Schau, E.M., Haskins, C., 2010. A framework for environmental analyses of fish food production systems based on systems engineering principles. Systems Engineering 13(2), 109-118.

Fields, G., 2009. Chapter seven- Making investment decisions: rate of return and net present value, Bottom line management. Springer.

Figari, M., Soares, C.G., 2009. Fuel consumption and exhaust emissions reduction by dynamic propeller pitch control, Analysis and Design of Marine Structures. CRC Press, pp. 543-550.

Fiskeriportalen, 2016. Fiskebåter- kvoter, fangst og posisjon. Available: <http://www.fiskeriportalen.no/fiskebater> (accessed 01.04.2016).

Fleddum, A.-L., 2016. Personal communication, In: Jafarzadeh, S. (Ed.). The Confederation of Norwegian Enterprise (in Norwegian: Næringslivets Hovedorganisasjon; NHO), Norway.

GFF, 2016. Reimbursement of mineral oil tax (In Norwegian: Refusjon av mineraljeavgift). Available: <http://www.garantikassen.no/no/ordningene/refusjon_av_mineraloljeavgift/> (accessed 28.04.2016).

Hop, H.B., 2016. Personal communication, In: Jafarzadeh, S. (Ed.). Norwegian Maritime Authority, Norway.

Høibye, G., 2012. The NOx fund- how does it work and what is its role. Available: <http://norwegen.ahk.de/fileadmin/ahk_norwegen/Dokumente/Presentasjoner/lng/HOIBYE_The_NOx_Fund_-_How_does_it_work_and_what_is_its_role_20.6.2012.pdf> (accessed 22.10.2014).

IGU, 2012. Natural Gas Conversion Pocketbook. International Gas Union (IGU), Oslo, Norway.

IMO, 2013a. Greenhouse gas emissions. Available: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx> (accessed 26.03.2013).

IMO, 2013b. Prevention of air pollution from ships. Available: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx> (accessed 21.05.2013).

Jafarzadeh, S., et al., LNG-fuelled fishing vessels: A systems engineering approach. Transportation Research Part D: Transport and Environment, 2017. 50: p. 202-222.

IMO, 2014a. Nitrogen Oxides (NOx)- Regulation 13. Available: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx> (accessed 03.12.2014).

IMO, 2014b. Sulphur oxides (SOx)- Regulation 14. Available: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-%28SOx%29-%E2%80%93-Regulation-14.aspx> (accessed 03.12.2014).

IMO, 2015a. Gas and low-flashpoint fuels code adopted by IMO Maritime Safety Committee (MSC), 95th session, 3-12 June 2015. Available: <http://www.imo.org/en/MediaCentre/PressBriefings/Pages/26-MSC-95-ENDS.aspx> (accessed 01.10.2015).

IMO, 2015b. Resolution MSC.391(95)- Adoption of the international code of safety for ships using gases or other low-flashpoint fuels (IGF Code).

IMO, 2015c. Resolution MSC.396(95)- Amendments to the International Convrntion on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW), 1978, as amended.

IMO, 2015d. Resolution MSC.397(95)- Amendments to part A of the Seafarers' Training, Certification and Watchkeeping (STCW) Code.

IMO, 2016. International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978. Available: <http://www.imo.org/en/OurWork/HumanElement/TrainingCertification/Pages/STCW-Convention.aspx> (accessed 10.02.2016).

INCOSE, 2015. System engineering handbook: A guide for system life cycle processes and activities, 4th ed. John Wiley & Sons.

ITF, 2013. STCW- A guide for seafarers taking into account the 2010 Manila amendments. International Transport workers' Federation (ITF), London, UK.

Jafarzadeh, S., Ellingsen, H., Aanondsen, S.A., 2016. Energy efficiency of Norwegian fisheries from 2003 to 2012. Journal of Cleaner Production 112, Part 5, 3616-3630.

Jafarzadeh, S., Ellingsen, H., Utne, I.B., 2012. Emission reduction in the Norwegian fishing fleet: Towards LNG?, *Second international symposium on fishing vessel energy efficiency (E-Fishing)*, Vigo, Spain.

Jafarzadeh, S., Pedersen, E., Notti, E., Sala, A., Ellingsen, H., 2014. A bond graph approach to improve the energy efficiency of ships, *ASME 2014 33rd international conference on ocean, offshore and Arctic engineering (OMAE 2014)*. ASME, San Francisco, California, USA.

Jetlund, A., 2016. Personal communication, In: Jafarzadeh, S. (Ed.). Cryomar AS, Norway.

Khakzad, N., Khan, F., Amyotte, P., 2012. Dynamic risk analysis using bow-tie approach. Reliability Engineering & System Safety 104, 36-44.

Kossiakoff, A., Sweet, W.N., Seymour, S.J., Biemer, S.M., 2011a. Decision Analysis and Support, Systems Engineering Principles and Practice. John Wiley & Sons, Inc., pp. 255-313.

Kossiakoff, A., Sweet, W.N., Seymour, S.J., Biemer, S.M., 2011b. Structure of Complex Systems, Systems Engineering Principles and Practice. John Wiley & Sons, Inc., pp. 41-67.

Kraack, M., 2014. MarTech LNG- Activities & Projects. Marine Service GMBH, Warnemünde, Germany.

Leveson, N., 2004. A new accident model for engineering safer systems. Safety Science 42(4), 237-270.

Leveson, N., 2011. Engineering a safer world- system thinking applied to safety. Massachusetts Institute of Technology (MIT).

Lin, C.-Y., Huang, T.-H., 2012. Cost–benefit evaluation of using biodiesel as an alternative fuel for fishing boats in Taiwan. Marine Policy 36(1), 103-107.

Jafarzadeh, S., et al., LNG-fuelled fishing vessels: A systems engineering approach. Transportation Research Part D: Transport and Environment, 2017. 50: p. 202-222.

Lindøe, P.H., 2007. Safe offshore workers and unsafe fishermen- a system failure? Policy and Practice in Health and Safety 5(2), 25-39.

Long, D., Scott, Z., 2011. A primer for model-based system engineering. Vitech Corporation, Blacksburg, Virginia, USA.

LR, 2012. Understanding Exhaust Gas Treatment Systems- Guidance for Shipowners and Operators. Lloyd's Register (LR), London, UK.

LR, 2015. Your options for emissions compliance- Guidance for shipowners and operators on the Annex VI SOx and NOx regulations. Lloyd's Register (LR), London, UK.

Marhaug, L.A., 2016. Personal communication, In: Jafarzadeh, S. (Ed.). Gasnor, Norway.

Martelli, M., Figari, M., Altosole, M., Vignolo, S., 2013. Controllable pitch propeller actuating mechanism, modelling and simulation. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment.

Martelli, M., Vernengo, G., Bruzzone, D., Notti, E., 2016. Overall efficiency assessment of a trawler propulsion system based on hydrodynamic performance computations, *The 26th international ocean and polar engineering conference (ISOPE-2016)*. ISOPE, Rhodes, Greece.

Martelli, M., Viviani, M., Altosole, M., Figari, M., Vignolo, S., 2014. Numerical modelling of propulsion, control and ship motions in 6 degrees of freedom. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 228(4), 373-397.

McGuinness, E., Aasjord, H.L., Utne, I.B., Holmen, I.M., 2013. Fatalities in the Norwegian fishing fleet 1990–2011. Safety Science 57, 335-351.

Mohn, H., 2012. LNG as ship fuel- operational experience and safety barriers, *Baltic Sea Days 2012*. German Presidency of the Council of the Baltic Sea States (CBSS), Berlin, Germany.

NHO, 2013. The NOx fund and the environmental agreement. Available: <https://www.nho.no/Prosjekter-og-programmer/NOx-fondet/The-NOx-fund/The-NOx-Fund-and-the-Environmental-Agreement/> (accessed 12.12.2014).

NHO, 2016a. Application for support to NOx-reducing measures- a guide. The Confederation of Norwegian Enterprise (in Norwegian Næringslivets Hovedorganisasjon; NHO), Norway.

NHO, 2016b. Unchanged payment rates. Available: <https://www.nho.no/Prosjekter-og-programmer/NOx-fondet/The-NOx-fund/News/2016/unchanged-payment-rates/> (accessed 20.04.2016).

Norges Bank, 2016. Exchange rate for US Dollar (USD). Available: <http://www.norges-bank.no/en/Statistics/exchange_rates/currency/USD/> (accessed 27.04.2016).

Norsok Standard, 1996. Common requirements- Life cycle cost for systems and equipment, O-CR-001,

Norwegian Directorate of Taxes, 2016. Taxes on mineral products etc.. 2016 (In Norwegian: Avgifter på mineralske prodkter mv. 2016). Oslo, Norway.

Norwegian Maritime Directorate, 2014. Guidelines on the NOx tax. Norway.

Notti, E., Sala, A., 2013. Propulsion system improvement for trawlers, Developments in Maritime Transportation and Exploitation of Sea Resources. CRC Press, pp. 1085-1090.

NP, 2013. Norsk bransjestandard for oljeprodukter (Norwegian industry standard for oil products). Norwegian Petroleum Institute (NP), Oslo, Norway.

Oliver, D.W., Kelliher, T.P., Keegan, J.G., 1997. Engineering complex systems with models and objects. McGraw-Hill, New York, USA.

Olsen, O.E., Lindøe, P.H., 2009. Risk on the ramble: The international transfer of risk and vulnerability. Safety Science 47(6), 743-755.

Jafarzadeh, S., et al., LNG-fuelled fishing vessels: A systems engineering approach. Transportation Research Part D: Transport and Environment, 2017. 50: p. 202-222.

Paltrinieri, N., Tugnoli, A., Cozzani, V., 2015. Hazard identification for innovative LNG regasification technologies. Reliability Engineering & System Safety 137, 18-28.

Parker, R.W.R., Hartmann, K., Green, B.S., Gardner, C., Watson, R.A., 2015. Environmental and economic dimensions of fuel use in Australian fisheries. Journal of Cleaner Production 87, 78-86.

Parker, R.W.R., Tyedmers, P.H., 2015. Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish and Fisheries 16(4), 684-696.

Pohl, E., Nachtmann, H., 2010. Life Cycle Costing, Decision Making in Systems Engineering and Management. John Wiley & Sons, Inc., pp. 137-181.

PSA, 2013. Principles for barrier management in the petroleum industry. Petroleum Safety Authority Norway (PSA), Norway.

Reid, R.C., 1983. Rapid Phase Transitions from Liquid to Vapor. Advances in Chemical Engineering 12, 105-208.

Rolls-Royce, 2016. LNG tanks. Available: <http://www.rolls-royce.com/products-and-services/marine/lng/discover/low-maintenance.aspx#section-systems> (accessed 01.05.2016).

SGMF, 2016. Sea change. Available: <http://www.sgmf.info/media/6715/sgmf_a4folder_lowres.pdf> (accessed 10.05.2016).

Ship & Bunker, 2016. Bergen bunker prices. Available: <http://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LSMGO> (accessed 28.04.2016).

SIGTTO, 2000. Liquefied gas handling principles on ships and in terminals, Third ed. Witherby Publishers, London, England.

SIGTTO, 2002. Liquefied gas carriers- Your personal safety guide. Witherby Publishers, London, England.

SIGTTO, 2011. LNG Shipping Knowledge- Underpinning Knowledge to the SIGTTO Standards, Second ed. Witherby Publishing, Edinburgh.

SIGTTO, 2014. SIGTTO Profile. The Society of International Gas Tanker and Terminal Operators (SIGTTO) London, UK.

Skatteetaten, 2016. NOx tax. Available: <http://www.skatteetaten.no/en/business-and-organisation/duties/environment/nox-tax/> (accessed 01.04.2016).

Skjervheim, A., 2012. Reduce emissions, expand potentioal- LNG the Norwegian experience. Available: <http://norwegen.ahk.de/fileadmin/ahk_norwegen/Dokumente/Presentasjoner/lng/SKJERVHEIM_Gasnor.pdf> (accessed 26.04.2016).

Sproles, N., 2001. The difficult problem of establishing measures of effectiveness for command and control: A systems engineering perspective. Systems Engineering 4(2), 145-155.

Sproles, N., 2002. Formulating measures of effectiveness. Systems Engineering 5(4), 253-263.

Stenersen, D., 2015. Personal communication, In: Jafarzadeh, S. (Ed.). MARINTEK, Norway.

Sumaila, U.R., Teh, L., Watson, R., Tyedmers, P., Pauly, D., 2008. Fuel price increase, subsidies, overcapacity, and resource sustainability. ICES Journal of Marine Science: Journal du Conseil 65(6), 832-840.

Tugnoli, A., Paltrinieri, N., Landucci, G., Cozzani, V., 2010. LNG regasification terminals: comparing the inherent safety performance of innovative technologies. Chemical Engineering Transactions 19, 391-396.

Tyedmers, P.H., Watson, R., Pauly, D., 2005. Fueling Global Fishing Fleets. AMBIO: A Journal of the Human Environment 34(8), 635-638.

Jafarzadeh, S., et al., LNG-fuelled fishing vessels: A systems engineering approach. Transportation Research Part D: Transport and Environment, 2017. 50: p. 202-222.

Tzannatos, E., Papadimitriou, S., Koliousis, I., 2015. A Techno-Economic Analysis of Oil vs. Natural Gas Operation for Greek Island Ferries. International Journal of Sustainable Transportation 9(4), 272-281.

UNECE, 2014. Protocol to abate acidification, eutrophcation and ground-level ozone. Available: <http://www.unece.org/env/lrtap/multi_h1.html> (accessed 20.10.2014).

UNFCCC, 2014. Status of the Doha Amendment. Available: <http://unfccc.int/kyoto_protocol/doha_amendment/items/7362.php> (accessed 17.10.2014).

Vílchez, J.A., Espejo, V., Casal, J., 2011. Generic event trees and probabilities for the release of different types of hazardous materials. Journal of Loss Prevention in the Process Industries 24(3), 281-287.

Wang, S., Notteboom, T., 2014. The Adoption of Liquefied Natural Gas as a Ship Fuel: A Systematic Review of Perspectives and Challenges. Transport Reviews, 1-26.

WinGD, 2015. Low- and high-pressure dual-fuel technology evaluation process; case studies for LNG carriers and merchant vessel, *Licensees Conference*. Winterthur Gas & Diesel (WinGD), Interlaken, Switzerland.

Winther, U., Ziegler, F., Hognes, E.S., Emanuelsson, A., Sund, V., Ellingsen, H., 2009. Carbon footprint and energy use of Norwegian seafood products. SINTEF Fisheries and Aquaculture,

Wold, M.C., 2016. Personal communication, In: Jafarzadeh, S. (Ed.). DNV GL, Norway.

Woodward, J.L., Pitblado, R.M., 2010. Other LNG Hazards, LNG Risk Based Safety. John Wiley & Sons, Inc., pp. 275-317.

Æsøy, V., Einang, P.M., Stenersen, D., Hennie, E., Valberg, I., 2011. LNG-fuelled engines and fuel systems for medium-speed engines in maritime applications. SAE Technical Paper 2011-01-1998.

Åsen, E.M., 2013. Norway: the NOx tax scheme. Available: <http://www.unece.org/fileadmin/DAM/env/documents/2013/air/wgsr_51/6_NOx-tax-Norway-geneva-april2013.pdf> (accessed 17.10.2014).