A novel approach to developing effective maritime regulations: The case of LNG cargo filling limits

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**ABSTRACT**

This paper introduces a novel approach to resolving a part of the fundamental problems encountered in the current practice of maritime regulatory frameworks. The novelty of the proposed method lies in a detailed and structured process that can examine and verify the appropriateness of a particular regulation in terms of integrating economic, environmental and safety impacts. Through its built-up database of approximately 440 LNG carriers in the world, the excellence of the proposed approach has been demonstrated by investigating the suitability of a controversial regulation related to the LNG cargo filling limit set forth in "the International code for the construction & Equipment of Ships carrying liquefied gases in bulk." A series of case studies have confirmed 169 LNG carriers currently are subjected to being placed under this issue. In this study, we identified ships’ key characteristics which would contribute to the increase in total costs associated with economic, environmental and safety impacts and presented the threshold between the opportunity costs and the severity of the regulation. The research findings have provided a managerial insight that may increase the reliability of maritime regulations by applying this pragmatic/analytical regulatory framework model developed in this research.

**INTRODUCTION**

Shipping is spreading, playing a pivotal role in connecting world affairs. Maritime transportation has a significant impact on domestic and international business across energy, infrastructure and economic growth (Jun et al., 2018; Saidi et al., 2018). Meanwhile, a growing awareness of the maritime environment and safety issues has brought about several global challenges to the marine industry. Focusing on maritime safety, the advancement of new technologies continually outdated the existing regulations, raising various industrial issues such as regulatory conflicts and ambiguities.

The sea-born trade is not an exclusive sector in any single nation or group. It is an industry born from international needs which require not only the international cooperation for environment and safety but also for substantial and diverse commercial interests. Over the last five decades, the regulatory regime has played a significant part in maritime economics. Inter-governmental bodies have gradually developed regulatory systems that deal with all aspects of the business; ship design, maintenance standards, crewing costs, employment, cooperation, overhead costs, taxes, oil pollution liability, environment, emissions and so on. However, the theoretical economic elegance of market measures in the modern shipping industry is often contrasted with the substantial inefficiencies of new and/or existing regulations (Bennett, 2000). Vickerman (2008) argued that regulatory conflicts could lead to significant inefficiencies that jeopardize the potential benefits of transportation service and productivity. Needless to say, in order to flourish the shipping business, maritime regulations should avoid confrontation, vagueness and inadequacy.

Given the fact that all regulations may have conflicting interests, such as increasing profits versus improved ethics or minimum risk, we need to better understand current issues and develop optimal regulatory models.

**Figure 1** shows the current maritime regulatory process with which most of maritime regulations have been enacted for ensuring the world fleets to be cleaner and safer. Maritime safety and environmental regulations are primarily proposed/rectified in cooperation with three major parties: the IMO (International Maritime Organization), flag states and classification societies.

One of the structural problems obtained in this figure is that while all parties represent the public interest rather than industrial business, they do not fully recognize the impact of regulation on marine business.

These regulations do not require the consent of business stakeholders who are excluded from the rule decision framework. On the other hand, increasing demand for roles and responsibilities from stringent regulations puts weights on shipping companies and cargo owners

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This pressure may potentially affect the long-term profitability and the viability of their business. Sometimes, too many rules lack great flexibility in procedural complexity or risk aversion bias (Nivola, 2010). The maritime SOX regulations declared in IMO MARPOL Annex VI Reg. 14 can be a good example. The stringent regulation charges higher construction or operational expenses to ship-owners. Those problems are neither negligible nor easily solvable, but all the attention of the researcher is necessary.

In the meantime, the current practices of developing regulations are more likely to take a conservative stance because those legislators are unwilling to take unpredictable risks. As a result, maritime regulations are often too simple and overly stringent than necessary. However, the real world is inevitably more complex than depicted in the regulatory models.

**Past research**

Several national and maritime group groups also raised concerns about the review process of IMO regulations. Their claims were documented and submitted to the IMO in 2015 (Jamaica). In 2017, IMO has introduced a strategic plan that includes the need to continually improve the IMO regulatory framework. They address the need to develop a legal framework that embraces new technologies and approaches without favoring or disrupting one technology over another. In addition, they propose the review of these approaches and their practices that will allow to improve the effectiveness of existing IMO devices, and better assess the need for new regulations that take into account the impact and benefits of the proposed measures. However, those strategic plans and guidance are abstract, and the detailed approaches are somewhat vague (IMO, 2017).

The question of how to develop a systematic approach to effectively developing and/or reviewing regulations still remains.

**Overview of regulation vs economy**

This section was intended to outline past research related to investigating the impact of regulation on the economy. Samuel Plimsoll firstly started his campaign against the notorious regulations in the 1870s (Stopford, 2013). The same resistance to strict regulations was found by many other researchers.

Hearn (1972) discussed problems and prospects in international maritime regulation. An emphasis of his
research was placed on the importance of the harmonisation between the regulations and maritime commerce. It was believed that the goal of the maritime regulations should be to ensure that shipping companies comply with the same standards of safety and environmental responsibility that apply to land.

To be specific, Wiswall (1982) has investigated the domestic impact of international maritime regulations and addressed the importance of uniformity of such regulations. Van Der Linden (2001) carried out an investigative study on the economic impact of maritime policies in German, whereas Lee et al. (2013) evaluated the quantitative impact of marine carbon taxes on the global economy. They argued policy making often leads to rigid and inaccurate results in maritime economy. Hermeling et al. (2015) conducted an economic and regulatory analysis of the EU trading system for marine pollution. Their conclusions implied that it seemed unable to achieve cost reductions effectively and to design systems compatible with international regulations.

Dong et al. (2014) and Sys et al. (2016) investigated the impact of IMO MARPOL Annex VI Reg. 14, SOx caps, on the maritime economy. They predicted the behavior of shipping companies in compliance with this regulation, clearly indicating the significant burdens on them. Then, their analysis suggested that the current regulation should be amended to keep intact of marine industry. Jiang et al. (2014) particularly estimated the expense to meet the SOx regulation: approx. 5,700,000 Euro for capital costs plus about 23,000 Euro annually for operating and maintenance if fitted with a scrubber system. Lähteenmäki-Uutela et al. (2017) proposed a comprehensive regulatory impact framework for socio-economic impacts that can be extended to other environmental regulations to support the needs of a consistent and reliable evidence-based maritime policy.

Woo et al. (2018) proposed to examine the environmental policy issues at the port of ecological and policy impacts on the port’s cost–benefit structure in both the economic and environmental aspects. They have concluded that policies inevitably resulted in costs for the parties involved, particularly the port itself. Dai et al. (2018) presented a model to investigate the operating costs charged by emission schemes on Asia-Europe routes. Study results showed the extra costs associated with regional emission systems and the potential for market distortions while emphasizing the complex impact of international environmental policies when considering market dynamics.

The adverse impact of regulation to the economy can also be found and was discussed in other transport sectors. For aviation, Adler and Liebert (2014) examined the impact of competition, ownership and economic regulation on airport performance and prices. With data envelope analysis, they measured the extra cost of environmental regulations. Littlechild (2018) argued the importance of the proper format and focus on airport regulation which can be evolved in consideration of economic and technology opportunities. In terms of the road transport economy, Çetin and Eryigit (2011) estimated the impact of new regulations on the taxi market, dealing with the dramatic increase in medallion prices or the value of taxi licenses. Albalate and Gragera (2017) investigated the sensitivity of the garage price affected by the curbside regulation. Martinez et al. (2018) addressed the shortcoming of the current regulations on the two Alanjama international roads and examined the appropriateness of current tolls. They introduced an enhanced regulation model which could improve the cost-effectiveness of road transport. In terms of railroad, Cantos and Maudos (2001) discussed the European railway system between regulation and efficiency. They argued that the stringent regulation worsened the railway company’s financial accounting. Concerning cost, they addressed the losses related to inefficient costs and revenue inefficiencies. Laurino et al. (2015) stressed the need to strengthen the demand for economically sound regulation by examining railroad models in 20 countries. The critical characteristics of each regulatory system have been collected and analyzed to provide a preliminary overview of the current case, both quantitatively and qualitatively.

Mellahi (2007) has reviewed the empirical evidence available in the economic literature. Most evidence points towards environmental regulations as having a negative impact on productivity growth. For pollution-intensive industries, this impact could be significant. Barbera and McConnell (1990) developed an approach to measuring the impact of environmental regulations on total factor productivity growth, which is less restrictive than a simple growth accounting approach. Research findings contend that this industry accounts for about 10–30% of the decline in productivity in the 1970s.

Huge claims about the negative effects of regulation on the economy have been found in past studies. If we consider the current IMO regulatory process, as discussed in the previous section, beneficiaries of strict regulation will be social and mass media but will add pressure on the economy.

**Overview of optimal regulatory framework**

The past literature has been in line with our argument that overly strict regulations might have negative impacts on the transportation business to some extent. There need to develop systematic models to investigate the adequacy of maritime regulations, thereby finding an optimal way to harmonise the safety and environmental regulations with the economy. To
achieve this, there have been some acknowledgeable attempts in transport sectors.

Bagheri and Nakajima (2002) strived to investigate optimal level of financial regulation under the gats under General Agreement on Trade in Services (GATS). Their research was focused on the regulatory competition and cooperation framework from the standpoint of capital adequacy and disclosure of information. Veljanovski (2010) stated that relatively simple economic theories could help to understand regulation, and regulators could provide practical tools to make regulation more effective and efficient. Molina et al. (2012) identified the problems of designing regulatory policies in the mineral resource industry and presented an alternative framework for overcoming them in the oil industry.

Meanwhile, the effectiveness of multi-criteria decision-making analysis (MCDA) was discussed across some novel research. Kiesling et al. (2012) used the MCDA method to support regularly assets, whereas Malloy et al. (2013) applied a similar technique for examining the alternative regulatory works in chemical regulations. They pointed out that MCDA could play an important role in the new prevention-based regulatory program because it can lead to transparent, objective and rigorous analysis with a common underlying understanding of the relative performance of alternatives and trade-offs. Schwenk-Ferrero et al. (2017) proposed the use of MCDA for a comparative assessment of nuclear waste management strategies, taking into account regional perspectives. Their work has shown that MCDA can support appropriate decisions on nuclear waste management policies.

In the marine industry, several attempts of using MCDA can be observed. In recent works, Jeong et al. (2018) and Jeong et al. (2019) applied the MCDA method to investigate the optimal marine propulsion systems. Ren and Liang (2017) investigated sustainable alternative marine fuels using fuzzy MCDA. In addition to the previous studies mentioned above, there are also vast research papers used MCDA to make appropriate decisions throughout industries.

Conversely, there seems to have no direct application of MCDA to address current regulatory conflicts in the marine sector. Given this, the study was motivated to employ an enhanced MCDA model to determine the appropriate level of regulation for LNG cargo filling limit problems.

**Approach adopted**

**Objectives**

Given this background, the point of this paper was to focus attention on the international context of international practices relating to rules that do not fit into today’s world economic reality. Besides, it was to address the issue of how maritime regulations could be better coordinated with the international shipping systems. We should ensure that additions and modifications to the regulatory framework are based on relevant statistics, research and analysis.

In this context, this paper was to introduce a novel approach that could contribute to developing practically desirable regulations. It was, therefore, to offer specific suggestions that could improve the sustainability of maritime shipping.

**Proposed model**

Figure 2 outlines the proposed model that presents an enhanced approach to developing new maritime regulations as well as validating existing ones in a systematic way. The methods in this model can be combined with multi-criteria decision-making analysis (MCDA) with big data analysis. This model and algorithm were implemented in the LabVIEW platform connected to the ship database.

The proposed model consists of four steps as outlined below:

- **Step 1: Identification of arguable regulations/scenarios**

  This step can be translated into “problem identification.” Regulations under issues, thereby all credible scenarios whose performances are subject to the comparison, are identified in this step. This includes the identification of key parameters that are closely related to the cost, environmental and risk impacts of those scenarios. There are no limitations on the number and scope of scenarios. Identification work is carried out with extensive data collection which is used as input parameters in Step 2. The types and boundaries of data will accord with the goals and scope of analysis.

- **Step 2: Analyses**

  At this step, we are to examine the performance of selected scenarios from the economic, environmental, and risk perspectives. The analytical formulas are encapsulated in each impact analysis, which is to interact with database collected in Step 1. The database will be formatted with a variety of process data related to energy consumption, emissions, costs and accidental records collected from various sources such as shipyards, manufacturers, ship-owners, literature, etc. Cost parameters for the economic analysis can be expressed as shown in Eq.1.

  \[ \text{ECI}_{ij} = C_{C_{ij}} + C_{U_{ij}} + C_{SC_{ij}} \]  

  The environmental analysis considers the following types and amounts of emissions that are produced during ship operation: CO\(_2\), NO\(_x\), HC, SO\(_x\) and PM (particular matter). The proposed emissions are regarded as major causes of marine pollution, so
that a string of international conventions and regulations are adopted to strictly curb them in ship activities. Those emission levels are then converted into monetary values which were obtained from previous EU research works (Maibach et al., 2008). Details of data sources and costs are to be discussed in section 4.1.

\[ E_{ij} = C_{\text{CO}_2_i} \times Q_{\text{CO}_2_i} + C_{\text{NO}_x_i} \times Q_{\text{NO}_x_i} + C_{\text{SO}_2_i} \times Q_{\text{SO}_2_i} + C_{\text{PM}_i} \times Q_{\text{PM}_i} \]  

Risk is expressed as a combination of the frequency of occurrence of an unwanted event and the severity of the incident so that the risk impact can be stated in Eq. 3. The frequency analysis is performed with the help of event tree analysis (ETA) to account for the escalating events (finally ignition) from the initial leak. The consequence impact is focused on the impact on humans, while ignoring property damages or social harm.

Figure 2. Outline of the proposed approach to enhance the regulatory framework.
\begin{equation}
R_{ij} = (F_{LRj} \times F_{IG_{ij}}) \times C_{LRj}
\end{equation}
\begin{equation}
C_{LRj} = C_{i} \times N_{ij}
\end{equation}

As with environmental analysis, the risk impact is converted to monetary value based on that the cost of the consequence of an unwanted event is estimated with the number of fatalities as described in Eq.4. Details of risk values and data sources are discussed in section 4.1.

- Step 3: Integration of analyses results

The total lifetime cost is expressed as an integration of three effects that represent the overall performance of the subject vessels under different scenarios. By pursuing the uniform unit of analysis, we can avoid the normalization process which is complex and demanding but leads to low confidence in decision-making (Jeong et al., 2019). Instead, we can take a step to add each impact together directly as shown in Eq.5.

\begin{equation}
TC_{ij} = ECI_{ij} + EI_{ij} + RL_{ij}
\end{equation}

- Step 4: Evaluation of the best practice with parametric analyses

To investigate some of the provisions in the maritime rules and regulations, “rule-makers’ approach’ is needed to grasp general observation from the series of analyses. If too case-specific studies (using designers’ approach) may fail to provide general observations, and the resulting research findings may be subject to a question of general applicability.

In this context, a parametric analysis has been adopted as the last step to determine the key parameters that affect the outcome, thereby evaluating the best practice for issues in provisions. In this process, the candidate parameters are input continuously to the analysis platform and the results are plotted as graphs to find common patterns and trends; for example, the greater ship tonnage is, the more fuel consumption. An example is depicted in Figure 3.

Once identifying key parameters related to overall cost growth, this paper then determines the threshold between the overall cost and the severity of the regulation. A general observation of trends can also bring about further discussion on the holistic cost and benefit across the scenarios. The research findings will be packaged in the form of quantified guidelines to improve current problems.

Case study

Previous sections have pointed out the current issues in regulatory frameworks and introduced an enhanced regulatory model comprehensively. To be specific, this

![Figure 3. Process of parametric analysis.](image-url)
Background of the regulation issue on LNG cargo filling limits

With the increase in the number of LNG carriers, the “the International code for the construction & Equipment of Ships carrying liquefied gases in Bulk” (IGC code) was first developed during the period from the late 1970s to the early 1980s. The code has provided an international standard for the safe transport of liquefied gas as a best practice at the time. Meanwhile, remarkable technological advances in the field of maritime LNG systems over the past 30 years have not been able to adapt to the prescriptive nature of this old-fashioned Code (ABS, 2014).

As a result, the IMO overhauled this old Code (IMO, 2011a, 2011b, 2011c), thereby adopting the new IGC Code in 2014 that carries various amendments, mainly related to the LNG cargo containment system. Most parts of the new IGC Code have been recognized for their successful reflection on best practices applied to the latest LNG carriers in the marine industry. However, some parts of this Code are controversial and require further investigation for their adequacy.

As shown in Figure 4, under certain static list and/or trim conditions, there is a possibility of the formation of trapped gas, which is known “vapour pocket,” in cargo tanks. If not managed properly, the vapour is more likely to expand its volume and increase the tank pressure. As a result, the cargo liquid can overflow through the vapour header or the tank pressure relief valve (PRV) exhausts.

To counter this accidental release, the original IGC Code restricted the LNG cargo in membrane type tanks from filling more than 98% if they could not meet specific safety requirements stated in Chapter 8 of the Code; the New IGC Code has similar regulations relating to filling the cargo. On the other hand, regulatory discrepancies are observed between the original and New IGC Codes with regard to “specific safety requirements”; New IGC Code has more stringent conditions than the original. As a result, despite the same membrane LNG cargo tank, an awkward situation arises where existing LNG carriers subject to the original IGC code can fill up to 98.5% of cargo, while new LNG carriers applicable to the New IGC Code should fill up to 98.0% (IMO, 2014).

This safety enhancement of the New IGC Code was initially borrowed from IACS Recommendation 109 that most classification societies and stakeholders could not adopt due to the raising issue on its appropriateness. This safety enhancement of the new IGC code was first borrowed from IACS Recommendation 109, and most classification associations and stakeholders have raised issues of conformity. Meanwhile, IMO rule makers who belonged to government agencies surprisingly adopted this recommendation for the new IGC code without verification procedures. Considering the perfect safety record of the LNG carriers without any accident related to the vapour release from the cargo tanks over fifty-year operations with 85,000 voyages and 170,000 port calls, it can be regarded as an intolerant decision for cargo owners (SIGTTO, 2016).

Investigation of filling limits

Step 1: scenario identification

As of 2018, approx. 430 vessels have been constructed since the first LNG carrier, MV Cinderella, 1965 in Figure 5(a). About the conflicting regulations, the number of subject vessels is to decrease to 169 ships in Figure 5(b); these provisions are only applied to the ships having membrane cargo containment systems.

As earlier discussed, this paper considered two scenarios in cargo carriage; Base scenario represents the case with 98% LNG filling limit to each cargo tank,
whereas Alternative scenario is 98.5% for the filling limit of LNG cargo tanks. These two scenarios are, then, applied to the 169 LNG carriers to obtain the proper guidance to mediate this dispute.

Figure 6 shows a simplified format of the sorted data for the LNG carriers from the list of World Register Fleet. They have been used to analyse the difference between the two regulations in economic, environmental and safety-related impacts. From the figure, we can understand the ship characteristics ranging from tank capacity to the voyage route will be regarded as input parameters for the parametric analysis.

**Step 2: Analyses Economic analysis.** Economic analysis was focused on estimating the extra cost converted from the difference in the cargo transported between the two scenarios. For instance, if a vessel was having the cargo capacity of 182,700 m³, the Alternative scenario would require some extra voyages for transporting the remainder. Hence, the operation costs for the additional voyages were taken into account the Alternative scenario. From the information collected from the shipping markets and companies, the following parameters were used for the calculation. In this

![Figure 5. World LNG carriers.](image-url)

![Figure 6. Data collection for the subject vessels based on the World Register Fleet.](image-url)
paper, we also adopted the average value of labor costs and the number of crew members.

- Fuel price: $473.5/t in Hong Kong (Ship & Bunker, 2018)
- Labor cost: $4,000/month/crew (by courtesy of a Korean LNG shipping company)
- Cost of ship chartering: $85,000/day (Corkhill, 2018)
- Number of ship crew: 30 persons

Figure 7 shows the results of the economic analysis. The red line refers to the reference line applicable to the Base scenario. The vessels were arranged from the smallest to the largest in different categories: (a) cargo capacity/(b) deadweight tonnage (DWT)/(c) engine size/(d) ship speed/(e) voyage length and (f) operational day at sea. For an example of Figure 7(a), the 1st vessel has the smallest cargo capacity (18,900 m³), and the 169th vessel has the largest one (1,479,700 m³). Meanwhile, analysis results suggested that there may have no or negligibly small relation between the overall costs and ship characteristics since no meaningful pattern was observed across the graphs.

Environmental analysis. Table 1 shows emission quantities from ship propulsion and their potential costs. From the ship operational profiles, the following emission parameters were considered for the analysis. Given that European countries have different cost values for each type of emission, this paper followed the UK standard costs (Maibach et al., 2008).

Results of environmental impact analysis are presented in Figure 8. In the same way as the economic analysis, the results were arranged from the smallest to the largest with the red reference line (Referring to Base Scenario). Looking into Figure 8(a), despite some outliers, we can find a proportional relationship.
between the overall cost and the engine size. From this, it can be deduced that the larger engine contributes more to the emissions in general. On the other hand, the other elements showed no or weak relations. A further investigation was made into the relation between the engine size and emissions. Figure 9 shows the quantities of emissions according to the engine size from the smallest to the largest. CO$_2$, SO$_x$ and PM emissions have clear relations with the engine size, whereas NO$_x$, CO and VOC emissions appear somewhat unrelated. However, if the steam engines were separated from the diesel engines, as shown in Figure 10 for diesel engines and Figure 11 for steam engines, we can obtain a better trend. Although the influence of various other elements in ship characteristics and operational profile did not allow us to see the perfect pattern, it seemed still meaningful to observe a general understanding that all emission types would be generally to the engine size.

Risk analysis. While, up to today, there has been no accidental release of the cargo through the vent mast due to the vapor pockets, Table 2 shows the historical records of accidents associated with LNG carriers. It is worthy of repeating that none of them led to LNG release from a cargo tank. That means

Table 1. Engine emission levels and potential costs (emission data was referenced from the emission test file 2018 by courtesy of MAN Diesel).

| Emission types | CO$_2$ | O$_2$ | CO | NO$_x$ | HC | SO$_x$ | PM (mg/m$^3$) |
|----------------|-------|-------|----|--------|----|--------|---------------|
| Qty (g/kWh)    | 446   | 1340  | 0.79| 8.76   | 0.39| 0.88   | 0.34          |
| Cost ($/ton)   | 24    | -     | -  | 3,900  | -  | 6,600  | 60,700        |

Figure 8. Results of environmental analysis (with monetary value).
such disasters may not directly contribute to what we were concerned; the frequency of vapour release in any situation is zero. Given that risk analysis can be expressed as the combination of frequency and consequence of particular accidents, the risk level associated with the filling limits can also be technically ignored.

On the other hand, it may be possible to reckon that the excellent safety record of LNG carriers may bring about a false sense of confidence with the future risks. It can also be perceived that as the number of LNG carriers rapidly increases, the frequency of LNG filling may also follow.

In this context, from the rule-makers point of view, this paper has to take a bit conservative stance in the risk analysis where all accidental frequencies were assumed to lead to the LNG release through vent mast if the events of collision, grounding and contact occur.

Figure 9. Results of environmental analysis (with emission quantities) in accordance with engine size.

Figure 12 shows the event tree leading to LNG incidents. Given that the LNG cargo space is regarded as a hazardous area where the source of ignition is strongly restricted, the level of the ignition probability was assumed to be 0.025 referring to the probability guidance (Jeong et al., 2017; Pesce et al., 2012). Since the surrounding condition of the deck is fully open, the expected result was flash fire, unlikely explosion. To take a conservative attitude, this paper assumed that all fatalities occurred in the case of flash fire.

For the process of risk analysis and conversion to costs, the following parameters are used.

- Cost of fatality: $3,000,000/person (IMO & IMO, 2002)
- Number of fatalities at sea: 30 persons (crews)
- Number of fatalities other than sea: 100 persons (crews + 3rd party persons)
Figure 13 plots the results of risk analysis in monetary value. One noteworthy point is the parametric sensitivity of voyage length (Figure 13(e)) and operational day at sea (Figure 13(f)) on the risk level; the vessels were arranged from the shortest to the longest time duration. It means the shorter voyage and the operation at sea can pose a higher risk to the third parties at port.

**Steps 3 and 4: Integration of analysis results and evaluation**

This step integrates the results of the analyses carried out in the previous step. Given that all impacts were converted into monetary values, the stakes of the results represent the total costs for each scenario. The integration process was, then, in collaboration with Step 4, the evaluation of the best scenario.

Moving back to our original question, this step was to evaluate the best practice to come up with the proper guidance to harmonies the two conflicting regulations related to the LNG cargo filling limit.

Given different characteristics across LNG carriers and their voyage profiles, the length of time at sea as shown in Figure 14(f) was shown the most influential parameter on the total costs claimed for those regulations.

From this, we can confirm that the time duration spent on each voyage is the key parameter to determine whether the Alternative case is appropriate or not. Moreover, we can offer guidance on the optimal practice of those regulations by introducing the marginal line. Figure 14(f) was magnified to Figure 15, which remarks the minimum, maximum and threshold sailing time per voyage. The figure shows the phase-changing length of time at sea is 9 days per voyage; the left-hand side of the marginal line represents the profitable area for 98% LNG filling (Alternative scenario), whereas the right-
hand side of the marginal line refers to the lucrative area for 98.5% LNG filling (Base scenario). This trend can be inferred from the results of the risk analysis in section 4.1.2; the longer ships stay in the ports, the more likely and severely it is that they will endanger people, thereby high-risk costs.

**Discussion**

Amid IMO presides over various maritime issues, the current regulatory process lacks the verification process which causes regulatory problems in all shapes; the way to legislate maritime rules so far has exceedingly passive changes. Such matters are to be identified, investigated
and resolved in proper ways. With rapidly advancing technology and systems of increasing complexity, the role of proper regulations is becoming ever more critical, and it is thought that there are and will be plenty of opportunities for this research can be extended.

The regulatory and legislative steps have been continually required to meet efficient maritime transport. In this regard, we must modify or abolish outdated forms which no longer appropriate for the design of current transportation regulatory systems. Also, we

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**Figure 12.** Event tree for LNG incidents (modified based on [Park et al., 2017]).

**Figure 13.** Results of risk analysis (with monetary value).
must adopt new means and new methods of meeting the changing needs of our industry.

Given this, this paper adequately addressed current concerns about maritime regulatory work as well as introduced a practical regulation model. The method given here is believed to give an insight into how we can incorporate rules into the systematic/analytical method as presenting a broader conceptualisation to strengthen the sustainability of the regulatory process at international levels.

In the analysis work, huge ship data was collected and stored in a database in vigorous efforts. The database was linked with the analysis algorithm implemented in the LabVIEW software. Therefore, the proposed approach can be said to provide an optimal solution comprehensively, consistent with large data analysis, which contributes greatly to understanding the general patterns and trends of the problem.

The case study introduced in this paper was used to confirm that the proposed model would be generally applicable. On the other hand, it is also worth mentioning that if abolishing the conservative stance on risk analysis, the threshold line is expected to be shifted to the left exceedingly. Further research remains to quantitatively improve risk analysis. Although the boundaries of cost parameters in reality are much more detailed than described in this paper, we believe that the range of parameters adopted here is sufficient for the scope of this study. Nevertheless, it should be said that different operational conditions may have some influence on the analysis results. In order to achieve a higher level of confidence in analysis results, sensitivity studies dealing with the impact of various parameters such as LNG fuel prices, fatality rates, accidental frequencies, etc., need to be carried out.
This research is highly believed a useful study since the IMO has recently developed and revised various rules, codes and guidance in cooperation with various third parties such as Associations of ship-owners, cargo owners, insurers, classification societies, and banks. Therefore, the proposed model can be applied to cases where the verification of provisions is urgent.

Conclusions

This paper provides valuable insight towards developing new regulations as well as investigating the adequacy of current regulations. Research findings can be summarized below:

(1) It demonstrated the excellence of the proposed model in terms of designing effective regulations in consideration of economic/environmental/safety impacts.

(2) By integrating the analytical model with the database, we were able to perform a wide range of parameter analyzes and contributed to the identification of key parameters and impact levels. Therefore, the general observations gained from case studies can dictate quantified recommendations for strengthening current regulations.

(3) Focusing on the case study, the research results can be highlighted below:

   i. The most sensitive parameter to the analysis of the LNG filling limit was the operating day at sea.

   ii. The conflicting provisions can be reconciled with the threshold where the provision of 98.5% filling limit is only valid for LNG ships having less than 9 days seagoing/each voyage.

   iii. Better commercial policies and market conditions were trusted to be a necessary prerequisite for future maritime regulatory work to reduce the burden on shipping companies.

(4) Finally, it is important to note that the use of the proposed model should not be limited to this case study, but be extended to a variety of regulatory regimes, not only maritime but also other industries where a systematic approach to legislative work is under-use.

Symbol lists

- $C_{\text{CO}_2}$: Cost of CO$_2$
- $C_{\text{FC}}$: Cost of fuel consumption
- $C_{\text{F}}$: Cost of fatality
- $C_{\text{L}}$: Cost of labour
- $C_{\text{LR}}$: Consequence of LNG release
- $C_{\text{NO}_x}$: Cost of NO$_x$
- $C_{\text{PM}}$: Cost of PM
- $C_{\text{SC}}$: Cost of ship chartering
- $C_{\text{SO}_x}$: Cost of SO$_x$
- $C_{\text{ECI}}$: Economic cost impact
- $C_{\text{EI}}$: Environmental impact
- $F_{\text{LR}}$: Frequency of LNG release
- $F_{\text{IG}}$: Frequency of ignition
- $N_{\text{F}}$: Number of fatalities
- $Q_{\text{CO}_2}$: Quantity of CO$_2$
- $Q_{\text{NO}_x}$: Quantity of NO$_x$
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