

## Article

# LNG Logistics Model to Meet Demand for Bunker Fuel

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**Abstract:** The main objective of this manuscript is to build a model for the distribution of LNG as a marine fuel in the southern Baltic Sea based on a genetic algorithm in terms of cost. In order to achieve this, it was necessary to develop, in detail, research sub-objectives like analysis of the intensity of ship traffic in the indicated area and analysis of LNG demand in maritime transport. In the first part of this study, the authors use data from the IALA IWRAP Mk2 and the Statistical Office in Szczecin to analyse the marine traffic density (by type of vessel) in the southern part of the Baltic Sea. LNG used as marine fuel reduces toxic emissions into the atmosphere. The authors specify the LNG fleet size and locations of LNG storage facilities in a way to ensure that the defined LNG bunker vessels can supply fuel to LNG-powered vessels within the shortest possible time period. The database contains a set of traits necessary to determine the optimal demand for LNG. The traits were developed based on an existing LNG fleet and appropriately selected infrastructure, and they represent existing LNG-powered vessels as well as LNG bunker vessels and their specifications. Based on the created LNG distribution model, were performed in Matlab R2019a software. An LNG distribution model was developed, which uses a genetic algorithm to solve the task. The demand for LNG for the sea area under analysis was determined based on data on the capacity of LNG-powered vessels (by type of vessel) and their distance from the specified port.

**Keywords:** energy security; transportation safety; transport infrastructure; traffic optimisation; traffic modelling



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## 1. Introduction

The ongoing measures to minimise the amount of toxic emissions released by seagoing vessels are aimed at meeting the following limits:

- As of 1 January 2015, the sulphur contents in bunker fuel must not exceed 0.1% in Emission Control Areas (ECA);
- As of 2020, the global limit for sulphur contents in fuel is 0.5%;
- The sulphur emission limit applicable in the European Union (EU) is 0.1–0.2%.

With a view toward meeting the environmental standards for reducing harmful emissions, bunker fuels in use comply with the requirements which have applied since 1 January 2020. Decision makers strive to support the development of alternative fuels, the one in highest demand being liquefied natural gas (LNG).

LNG is gas that has been cooled to a temperature of  $-162^{\circ}$  and converted into liquid [1]. The volume of LNG is ca. 600 times lower than that in a gaseous state; therefore, it is much easier to transport and store. This is especially important in long-distance transportation where a pipeline is not available. When transporting LNG across a long distance, the principles of rational management are applied (such as, e.g., low cost—economic effectiveness) [2]. LNG is imported and delivered by pipelines and by sea. Characterised by greater flexibility, transport and delivery by sea helps to meet the fast-growing demand for LNG. The increasing demand, on the other hand, drives the development of new technologies. For example, a recently implemented LNG offshore transfer and delivery system ensures safe transshipment of cargo, acting between supplying and receiving vessels [3].

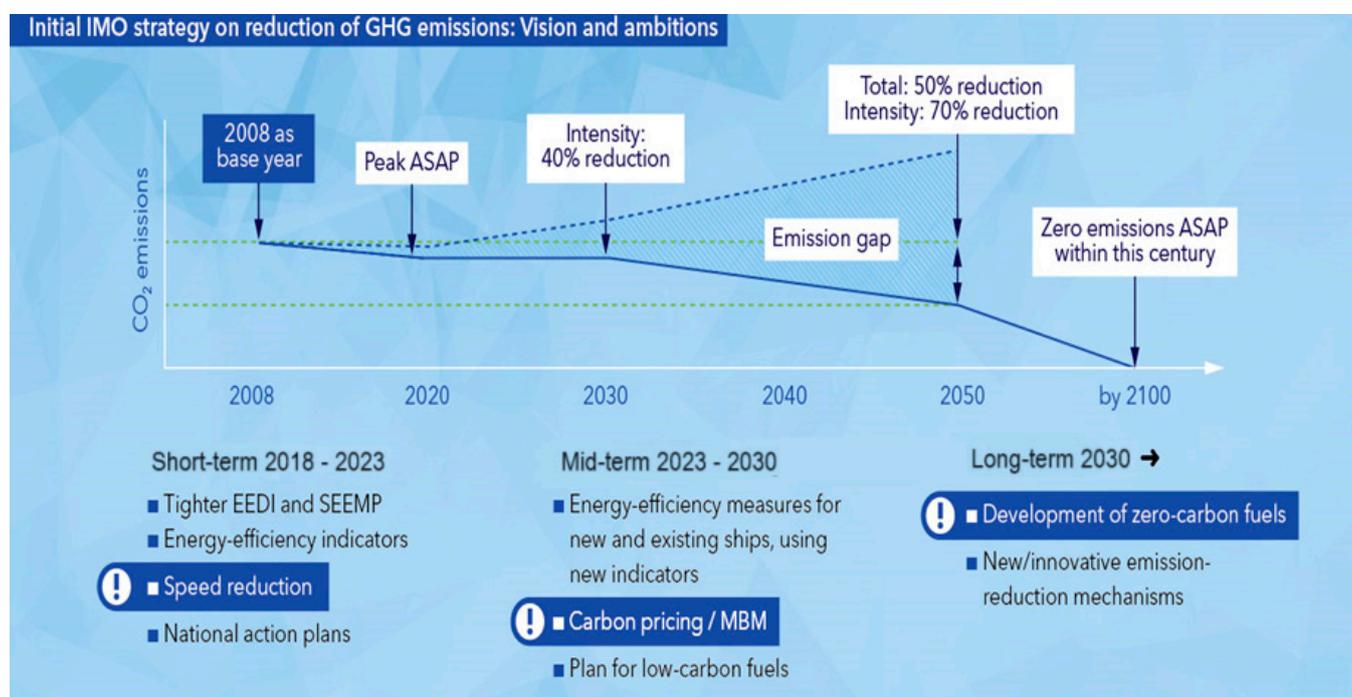
The LNG installations in use in waterway and land transport vary in size by an order of magnitude, from huge facilities used in maritime and rail transport to small installations in delivery vans. This makes LNG a low-emission fuel of great potential in the forthcoming decade [4].

Owing to its numerous advantages (including, without limitation, low toxic emissions into the atmosphere, i.e., the environmental factor), LNG is considered an alternative fuel in view of the necessary reduction in greenhouse emissions. LNG usage is growing in industry as well as in heavy transport. More and more enterprises use gas-powered heavy goods vehicles (HGVs) to leverage the economic benefits from low LNG prices [5–7]. LNG trade is growing in importance in the global natural gas market also owing to its competitive price, compared to the prices of fuel delivered by pipelines [8–10].

Many of the newly discovered gas extraction fields are located at a distance from the main transfer routes via pipelines. This fact, as well as an increase in the share of LNG in maritime transport, are the main drivers behind the dynamic growth of the LNG market. Previously, the natural gas market relied primarily on regional connections. The evolution of international economic relations has led to the creation of a global LNG market [11–13].

According to statistical data, the maritime sector generates more than 940 m tonnes of CO<sub>2</sub> annually, which constitutes ca. 2.5% of global greenhouse emissions [14–16]. Compared to heavy fuel oil (HFO)/marine gas oil (MGO), LNG generates less pollution, since the process of gas burning produces a smaller amount of toxins, such as CO<sub>2</sub>, sulphur oxides, nitrogen oxides, and dust.

National energy strategies are highly influenced by the EU's climate and energy policy, including the long-term vision of Europe becoming a climate-neutral continent by 2050 (Figure 1). The climate- and energy-related goals pursued by the EU pose challenging requirements of transformation to business entities.



**Figure 1.** Forecast reduction of greenhouse gas emissions [17].

In the forthcoming years, demand for natural gas and crude oil will be satisfied mainly through imports. The increasing use of biofuels and alternative fuels (including, without limitation, electricity, LNG, CNG, biomethane, and hydrogen) is bound to reduce that demand [18,19]. LNG is a key commodity on the global natural gas market. In view of the expected growth in the world's demand for natural gas in the forthcoming years,

diversification of supplies is of crucial importance for national energy security. Transported by LNG carriers, LNG is stored in specialised storage facilities [20–22].

In 2006, Poland launched the construction of its first LNG terminal—the President Kaczyński LNG Terminal in Świnoujście. The terminal fully meets the demand for LNG in the region and handles bunkering operations and supplies fuel to vessels operating in the Baltic Sea. In mid-2016, the LNG regasification terminal in Świnoujście received its first commercial LNG supplies, which was a milestone in the diversification of Poland’s gas supplies [23,24]. The construction of the LNG infrastructure was a breakthrough in the meeting of requirements specified in the EU’s Sulphur Directive in the region and boosted Poland’s economic development and strengthened the energy policy of EU countries. The LNG terminal receives gas supplies from Qatar, Norway, and the USA, to mention just a few sources [25]. The share of LNG in natural gas consumption may reach even 30% in the forthcoming years. Poland’s LNG terminal is a major facility ensuring security of natural gas supplies in Poland as well as neighbouring countries. This is a unique facility of this size in Central Europe.

There is no doubt that, owing to a wide array of applications, properties, and factors shaping the economy and market, the global importance of LNG is on an ongoing upward trend [26]. The LNG-powered transport fleet is growing year-on-year. Therefore, there is a burning need to extend existing LNG facilities or construct new ones to satisfy the demand for LNG while complying with the principles of rational management, including economic optimisation. Supplying LNG to end users is of paramount importance and involves a necessary development of transfer, distribution, and storage infrastructure.

The main purpose of this paper was to create a model for the distribution of LNG as a navigation fuel in the southern Baltic Sea based on a genetic algorithm in terms of cost. It was necessary to develop, in detail, the following research sub-objectives:

- Analysis of the intensity of ship traffic in terms of its size and technical parameters;
- Analysis of LNG demand in maritime transport;
- Development of a model for the distribution of LNG as a marine fuel for different ship sizes.

## 2. Literature Review

Liquefied natural gas is a liquid, high-methane, cooled gas, purified from humidity, CO<sub>2</sub>, nitrogen, and heavy carbohydrates. It is odourless, colourless, non-toxic, and easy to store and transport. Its main ingredient being methane, it also includes ethane, propane, and butane [27,28].

Compared with conventional fuels, LNG has a great number of advantages. Unparalleled in efficiency, high performance, and cost-effectiveness, it is safer and more environmentally friendly than other alternative fuels. Used as fuel, LNG helps reduce emissions by as much as 90%, and the process of liquefaction is emission-free. LNG’s unparalleled toxic emissions performance and negligible environmental impact are factors of utmost importance in mitigating the climate crisis. LNG produces and carries far fewer pollutants into the atmosphere than coal, oil, or other fossil fuels, thus helping to reduce CO<sub>2</sub> emissions. Composed of 95% methane and 5% other components, it is non-toxic and non-corrosive. In contact with air, LNG evaporates and dilutes and, thus, is less harmful to the environment than crude oil or LPG. LNG will never contaminate water or soil, even in the event of a spill. Moreover, modern regasification terminals have professional safety systems and implement procedures ensuring a safe regasification process.

In the process of liquefaction, natural gas is purified from undesired substances, such as carbon dioxide, nitrogen, a mixture of propane and butane, and water [29]. Liquefying technology reduces its volume and is also applied to increase the safety of transport and consumption [30,31]. The method consists in changing the form of gas to liquid. This is achieved by applying appropriate pressure and temperature below critical levels. During the process, the gas is purified from water, carbon dioxide, and nitrogen, in order to eliminate solid particles [32,33].

LNG facilities providing fuel bunkering services can be installed on the land as well as offshore. An important aspect of LNG distribution is the duration and methods of storage [34,35]. The location of LNG facilities and the fuel storage process are paramount for energy security and risk assessment [36], as well as for economic aspects and streamlined distribution management. On a national level, the accomplishment of an investment project consisting in the construction of LNG bunkering and storage infrastructure translates to reduced dependence on gas supplies. In developed countries, such an investment is bound to improve flexibility of facility operations and create growth in the demand for LNG on the part of seagoing vessels and commercial fleets on the land. Moreover, it ensures greater security of natural gas supplies to the national gas transmission system, resulting in improved energy efficiency. The development of an LNG infrastructure facilitates the development of new services, which in turn triggers growth of the natural gas market [37].

The recent years have seen the appearance of HGVs which run on LNG. In 2020, the number of LNG-powered passenger cars and delivery vehicles in Poland was 4682. In May 2020, 101 new and second-hand LNG-powered vehicles were registered, a drop by 40% on 2019. The decrease in the number of LNG-powered vehicles registered was caused by the still relatively small number of LNG filling stations [38].

The use of LNG fuel in passenger cars and HGVs is determined by the number of LNG filling stations. The development of LNG technology is stalled due to a lack of well-functioning distribution networks. LNG distribution stations are responsible for, inter alia, maintaining safe technical parameters of intermodal, cryogenic LNG tank containers over a long time period [39,40]. Storage of LNG in cryogenic tank containers makes it possible to distribute LNG to end users by all possible means of transport and—as a result—improves the availability of LNG fuel. Construction of the infrastructure should be accompanied by the development of new technologies—innovative, lightweight tanks (especially those intended for use in passenger cars and delivery vans), to ensure that proper parameters of LNG are maintained over a long term.

The natural gas market sees a demerging of the small-scale LNG sector where LNG fuel is supplied in road and rail tankers and cryogenic containers. The main customers of the small-scale LNG sector are food manufacturing companies and the tourist industry, who use LNG for heating and technological processes. The benefits include lower emissions of CO<sub>2</sub> and other toxic compounds causing smog. This market segment relies on the so-called island distribution zones, built in areas which are not connected to the national gas distribution network. A small, closed network built in such an area is supplied with fuel from a local regasification station, where LNG is delivered by means of road tankers. LNG is also used in areas which have access to the national gas distribution network, but the demand for gas is bigger than the transmission capacity of the existing pipelines. There, regasification stations help meet the demand from end users.

Owing to its properties and wide array of applications, LNG is part of supply chain processes. Distribution of LNG is performed in stages ensuring streamlined, quick, and effective flow [41]. Technical aspects, which comprise the selection of suitable means of transport, play a vital role in the LNG distribution chain. Means of transport are of paramount importance for proper performance of the entire supply chain [42]. A transport fleet capable of satisfying the demand in the logistic process is a priority to ensure security of supplies and hedge against anticipated threats [43].

The above considerations lead to a conclusion that LNG terminals play a key role in the LNG logistics chain. In combination with a suitable vehicle fleet and infrastructure, LNG terminals ensure access to the fuel [44]. One of the principal responsibilities of each state administration is to ensure economic security including, without limitation, energy supplies. Direct access to fuel fields is equally salient, as it translates to fuel unit prices, which are of key importance for end users as import costs determine the final purchase price [45–48].

As gas fuel, LNG presents the following advantages:

- Small fuel consumption and low price;

- Toll-free driving on motorways in Germany (significant for HGVs);
- Longer driving range on a full tank;
- Simpler engine design, lower failure rates and operating costs;
- Significantly lower CO<sub>2</sub> emissions.

Its disadvantages are as follows:

- Cryogenic tank limiting the range of transport;
- No possibility of a long stop-over (the properties of the fuel deteriorate);
- Low immunity to tank failures;
- Lack of refuelling infrastructure.

The use of LNG on marine vessels has been on an upward trend recently, especially in Emission Control Areas (ECA). MARPOL (International Convention for the Prevention of Pollution from Ships) has implemented more stringent regulations on the use of diesel fuel for marine vessels, prompted by the high sulphur content in diesel fuel, which is a major contributor to environmental pollution. Shipowners have the freedom to choose a solution to comply with the regulations. The range of choice includes, without limitation, includes the following:

- Low-sulphur diesel fuel, such as ULSFO (Ultra-Low-Sulphur Fuel Oil) or MGO (marine gas oil), which entails high fuel purchase costs;
- Fuel purification equipment;
- An LNG fuel system.

Considering the economic and environmental benefits, the most commonly applied solution on seagoing vessels is an LNG fuel system. Switching to LNG as marine fuel is increasingly supported across the world. Liquefaction of natural gas is considered the best new technology for the maritime industry, as LNG as marine fuel helps reduce sulphur oxide emissions by ca. 90–95% and CO<sub>2</sub> emissions by 20–25%, compared to conventional fuels [49,50]. LNG is used, without limitation, as follows:

- In areas under strict control of sulphur emissions (ECA);
- On short passages, since LNG tanks require voluminous storage space, and LNG has a limited storage duration before it starts to lose its properties;
- In cabotage;
- On vessels providing offshore services, such as ferries or tugboats, which sail on fixed routes;
- Where shipowners pursue an economic policy of rational management;
- In areas offering LNG bunkering services;
- On vessels where conversion from a conventional fuel system to an LNG-powered system is feasible;
- By shipowners who aim to modernise their fleet;
- By shipowners who have a high environmental awareness.

Considering its huge potential not only as marine fuel but also in other economic sectors, LNG should be included in energy and climate agendas of all countries. Its use fosters the development of the LNG infrastructure, which may include the following [51–54]:

- The construction of LNG liquefaction facilities using technologies which leverage the potential of the transmission network: a fast growth of the LNG market can be supported only if all the supply channels are engaged (energy-efficient gas liquefaction facilities using the potential of high-pressure gas pipelines can help improve energy efficiency of the transmission system and expand the range of services offered);
- The construction and operation of an offshore LNG bunkering infrastructure or expansion of the existing LNG bunkering infrastructure: the development and modernisation of ship bunkering systems, dictated by the applicable legal regulations as well as the growth of the LNG market (the process is bound to support expansion of the existing LNG bunkering infrastructure in anticipation of a spike in demand for LNG bunkering services);

- Combined Heat and Power (CHP)—improving the regasification capacity of LNG terminals to increase natural gas imports; this will improve operational flexibility and help introduce new functionalities (e.g., further expansion if recommended, based on market analyses);
- An intermodal LNG logistics hub: expanding the reach of services rendered by LNG terminals, possible implementation of the ‘virtual pipeline’ service—transportation of high LNG volumes across long distances, accompanied by improved effectiveness of services provided by LNG terminals (resulting in a greater significance in the region’s economy), supply of LNG to peak shaving stations supporting the national transmission system, and satellite regasification;
- Peak shaving regasification stations: LNG supplied to areas where the existing grids have insufficient transmission capacity—ensuring temporary or permanent gas supplies to end users who do not have access to an LNG facility (the creation of an infrastructure foundation, e.g., ISO container handling hubs);
- LNG transfer to, e.g., vehicle filling and LNG bunkering stations, etc.;
- ISO containers: intermodal gas transport;
- Ensuring quick and reliable LNG handling and bunkering;
- Improving offshore LNG regasification capacities: the rapidly growing LNG market needs a transmission infrastructure to meet the expected increase in demand, e.g., the construction of a floating LNG regasification terminal.

In order to increase the use of LNG across the global economy, the existing fleet and infrastructure must be modernised or new vehicles purchased and new LNG distribution facilities built [55,56]. LNG is the most preferable of all the alternative fuels in the shipping industry [57], as it helps reduce, most importantly, toxic emissions, thus eliminating the need of exhaust gas treatment [58].

Despite a complex process of adaptation of the fuel system to LNG, the number of LNG-powered vessels is on an upward trend. The benefits from the use of LNG in the maritime economy are various, from its non-toxic, non-corrosive, and odourless properties [59], through reasonable prices (i.e., in specified market conditions), to the elimination of secondary gas treatment facilities, such as selective catalytic reduction (SCR) units [60]. LNG-powered vessels are characterised by an improved capital return factor (CRF) and life cycle cost (LCC), where vessel mileage, fuel price, life cycle, and the gas fuel system are variables. It follows from research that where the passage time is short and the fuel price high, boil-off gas (BOG) reliquefaction may be the optimal solution [61].

The forecast for the growth of the LNG-powered fleet in maritime transport is promising [62,63]. A considerable growth in demand for LNG has been observed in areas covered by strict sulphur emission control [64,65], following from the introduction of environmental regulations aimed at improving air quality.

A number of methods which can be potentially applied to create an LNG distribution model are available in the Polish and foreign bodies of literature of the subject. All of them are based on genetic algorithms and related to transport branches other than maritime transport [66–70].

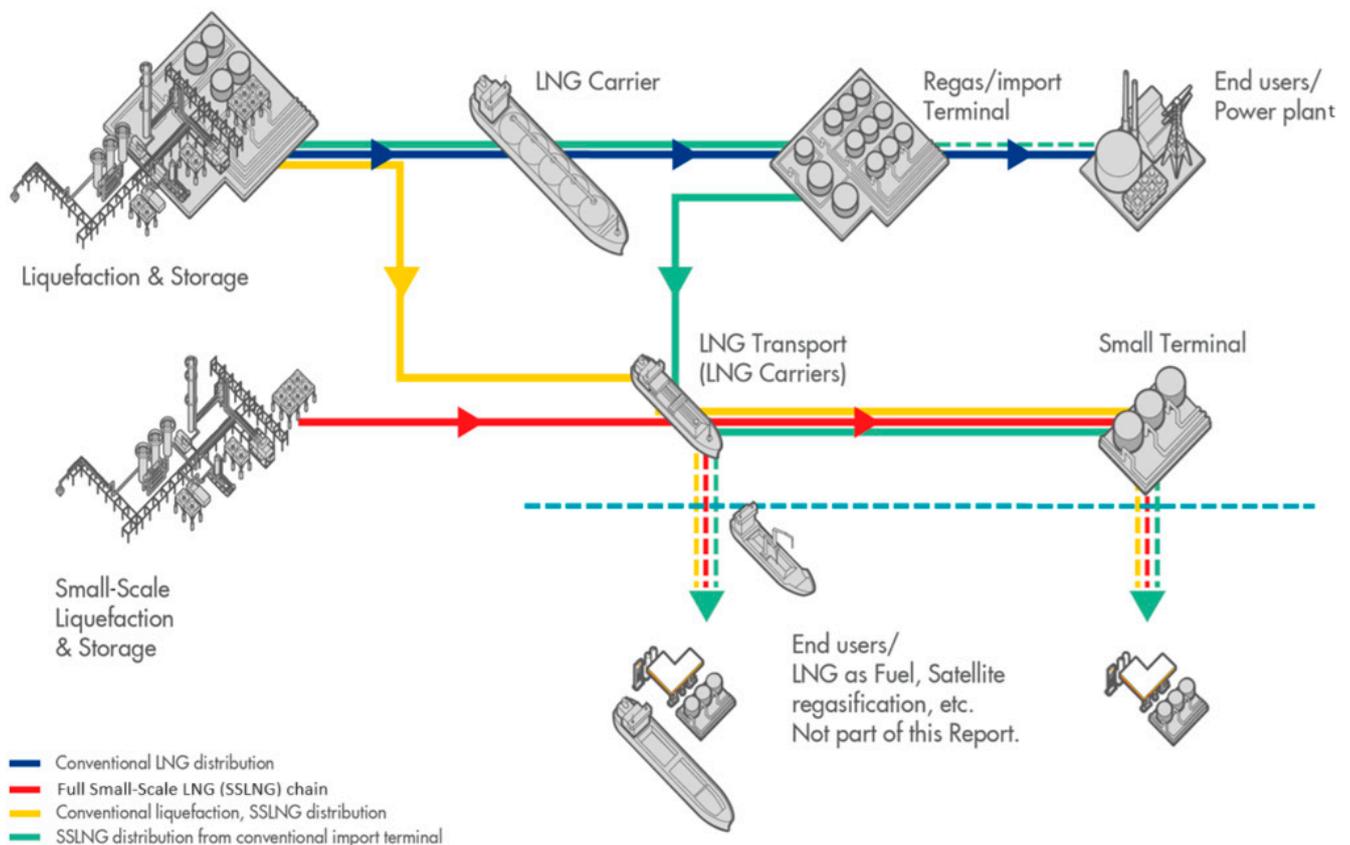
The use of LNG for propulsion of marine transport units was the first step in the development of LNG. This process proved to be a breakthrough in meeting the requirements of the Sulphur Directive. The availability of liquefied natural gas, together with the restrictions of the directive, led to an increase in demand for LNG resulting in the dynamic development of the LNG market in the maritime sphere. A significant role in influencing the development of maritime sectors is played by LNG distribution, where the problem of supplying vessels with LNG arises. The use of LNG as marine fuel is underinvestigated in the literature. There is no research into proposed or implemented models of offshore or land-based LNG distribution and the expected number of LNG-powered vessels. However, there is research providing characteristics of LNG carriers, LNG bunker vessels, as well as LNG ports which either render or are planning to render bunkering services [71]. No results of research into real demand for LNG as fuel across various sectors of the global economy

have been published, neither is currently performed research into minimisation of LNG distribution costs covered in the literature. Last but not least, no research into optimisation of LNG distribution networks with the use of scientific methods or optimisation techniques has been described in the literature of the subject. Therefore, in this paper, the authors investigate LNG distribution taking into consideration the environmental aspects, such as reduction in toxic emissions into the atmosphere, of which vessels are the largest emitters.

Research results acknowledge the impact of fuel price fluctuations on investments and environmental performance, i.e., a 33% reduction in CO<sub>2</sub> emissions owing to the use of the LNG dual-fuel marine engine [72]. In view of the increased environmental awareness in the maritime sector, LNG-related investments are highly required, as they are bound to improve air quality.

### 3. Materials and Methods

There are a number of solutions which can be applied in planning LNG distribution in the gas supply chain (Figure 2).



**Figure 2.** SSLNG offshore distribution network [65].

The diagram above presents an example of an LNG distribution network, summarised as follows:

- The blue line represents a conventional (large-scale) LNG distribution path: storage and liquefaction → LNG tanker → regasification/imports terminal → end users/power plants,
- The red line represents liquefaction at a small terminal, i.e., a traditional SSLNG distribution chain: small terminal → transport of LNG (smaller volumes of LNG are carried using small tanker vessels, HGVs, or rail vehicles) → small terminal → end users/LNG as fuel/LNG dispensers,

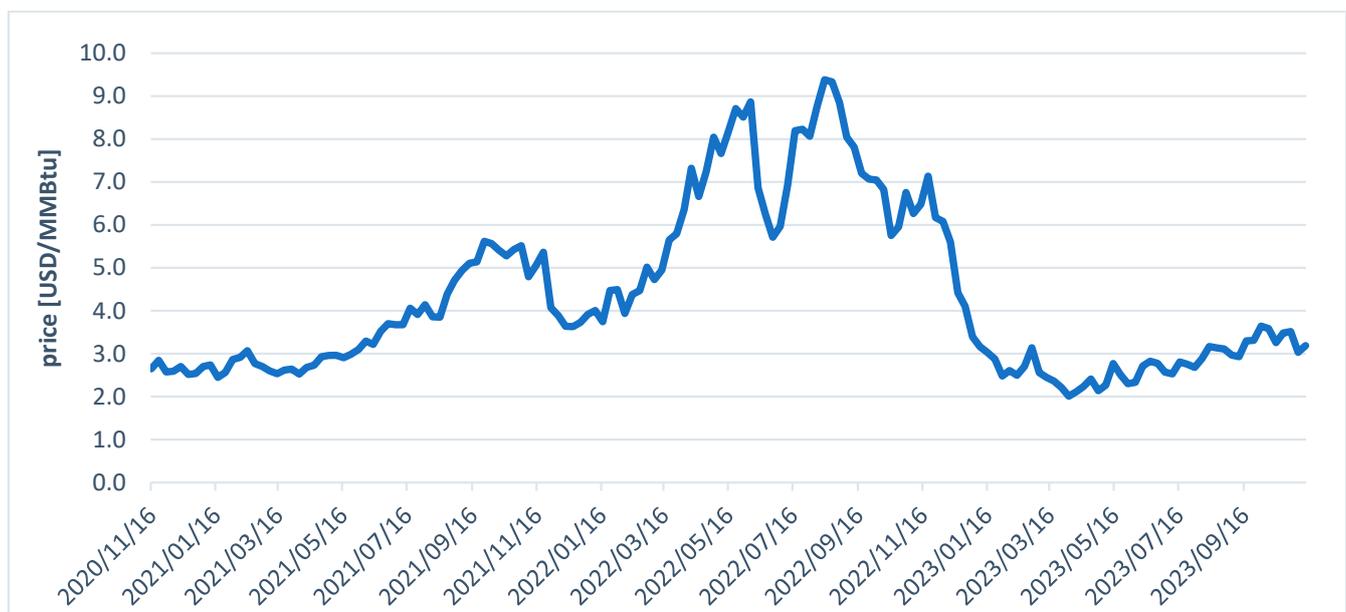
- The yellow line represents SSLNG liquefied in the conventional process and the subsequent distribution: storage and liquefaction → LNG transport → small regasification/imports terminal → end users/LNG as fuel/small LNG dispensers,
- The green lines represent the following:
  - Solid—demand for LNG from small LNG terminals (no regasification, use of imports terminals);
  - Dashed—LNG transmission from regasification and import terminals to a local power plant (or a distant power plant, not connected to the gas transmission network).

It is worth noting here that end users in the SSLNG supply chain can receive supplies from large LNG storage facilities as well as small LNG terminals.

In view of the necessary reduction in toxic emissions from marine engines, both engine manufacturers and shipowners are looking for solutions which ensure that the requirements set out in the Sulphur Directive are fulfilled.

The literature show results of an environmental assessment of eco-friendly fuels, namely marine gas oil (MGO), LNG, and hydrogen, performed for a ferry coaster. It follows from a comparative analysis that MGO and LNG produce less NO<sub>x</sub> and SO<sub>x</sub> emissions than hydrogen, whereas LNG produces the least CO<sub>2</sub> emissions of the three fuels under analysis [73]. An analysis of data has shown that compared to LNG, the use of hydrogen fuel is bound to increase global warming potential by 10% [74]. Therefore, looking to comply with the environmental standards, the industry players show justified interest in the use of desulphurised fuel, such as LNG.

An analysis of the LNG prices over the past three years has shown significant fluctuations (Figure 3). An upward trend can be observed for the period of 12 months starting from the beginning of 2020. A spike in prices can be observed at end of August and beginning of September 2020, as well as in autumn 2021, caused by a forecast of severe winter and insufficient supplies of LNG to the market. The demand for LNG in that period hit a record high and could not be satisfied by national stocks, depleted during an exceptionally cold spring when LNG consumption surged.



**Figure 3.** LNG prices from 16 October 2020 to 13 October 2023.

LNG is widely used across many sectors of the economy, including, without limitation, the electric power sector. The year 2021 saw insufficient wind to effectively power wind turbines. Countries which relied heavily on wind turbines for their energy security had to

increase expenditure on other energy sources. LNG, similarly to wind, is a green fuel. In that period, many countries increased purchases of LNG for power plants.

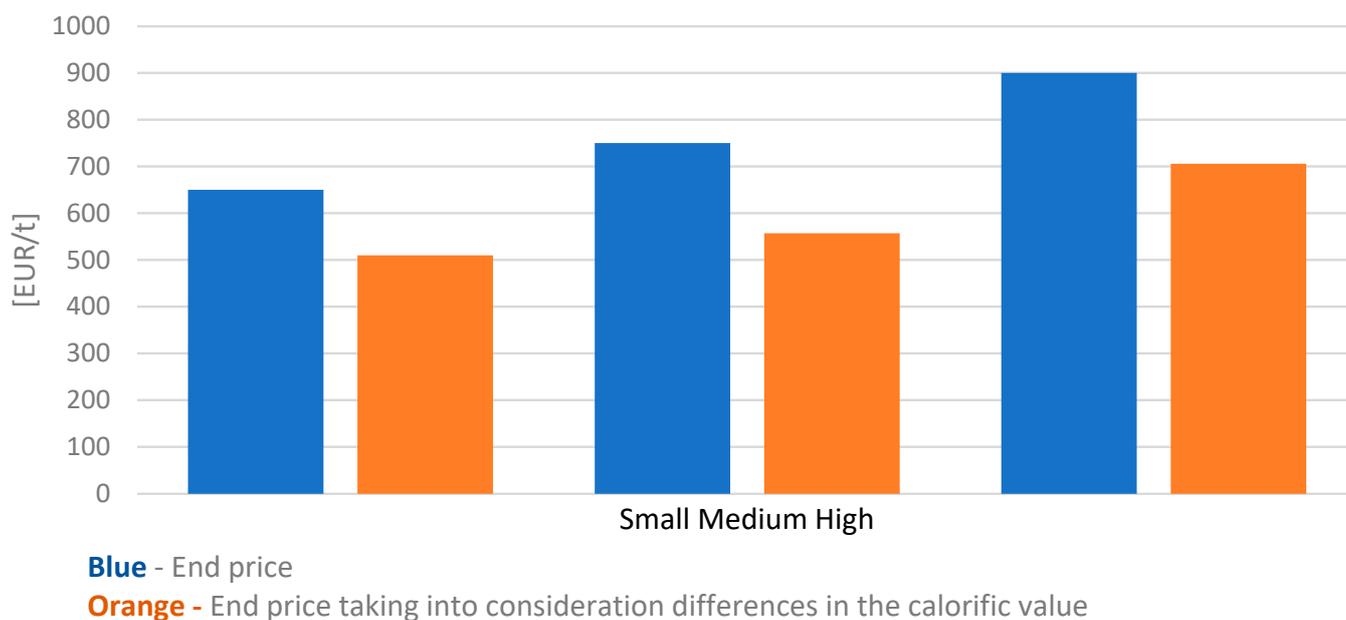
In January 2023, the available stocks of LNG and a low demand for heating power balanced out the LNG market price which plummeted to ca. USD 2.6000/MMBtu [75–77].

The current upward trend of LNG prices is related directly to the increased demand for heat and electricity. LNG consumption is also influenced by its price for end users (Table 1).

**Table 1.** Cost, by participants of the LNG distribution chain.

PRICE	Cost [EUR/t]		
	Imports	LNG Exports as Bunkering Fuel	End User
Small	320	430	650
Medium	450	550	750
High	580	680	900

Taking into consideration differences in the calorific values between MDO (42,700 kJ/kg—100%) and LNG (54,700 kJ/kg—128% MDO), the end user price is reduced by, respectively, ca. 22% for the small price, 26% for the medium price, and 22% for the high price (Figure 4).



**Figure 4.** Comparison of the end-user price with the price calculated taking into consideration differences in the calorific value.

The entire LNG supply chain is strongly affected by insufficient LNG distribution infrastructure. Another important factor is the price of LNG. Effectiveness of an LNG terminal can be assessed and the minimal LNG price determined:

1. For fixed values of input variables (Table 2):

**Table 2.** Estimated fixed values of input variables, used in calculations.

Input Variable	Fixed Value of the Input Variable
Period under analysis	15 years
Price of LNG as bunkering fuel (transport service included)	450 [EUR/t]
Max. transport route (one way)	20 Mm
Purchase price of LNG as bunkering fuel	450 [EUR/t]
Insurance of the infrastructure (on an annual basis)	0.4% (of the initial value)
Max. transport route (one way)	20 Mm
Discount rate as of 1 January 2020 (2.84% (1.84% + 1 p.p.))	8.0%
Income tax rate (in line with general principles of taxation)	19%
Regasification terminal amortisation and/or depreciation	10%
Regasification terminal throughput	Q = 1000 m <sup>3</sup> /h
Minimal rate of return [(1 + annual rate of return) – 1 × 100%]	10%
LNG consumption for technological processes + losses	0.5%
Capital expenditures (e.g., facilities, port and gas infrastructure, documentation, preparation of the investment project)	500,000.00 €
Maintenance	EUR 2500.00/1 year
Facility operation and surveillance	EUR 4500.00/1 year
Materials + energy	EUR 2000.00/1 year

2. For random input variables:

- A. Fixed costs of the distribution chain: 56.6% (amortisation and/or depreciation, taxes);
- B. Variable costs: 43.4%.

The above analysis is applied in enterprise valuation, in financial risk management, and in many other sectors of national economies. It can also be used to:

- Determine the beta coefficient variability—required to determine the cost of equity;
- Evaluate derivatives, e.g., contracts;
- Forecast interest rates, market risk, etc.;
- Assess viability of investment projects.

With reference to the maritime sector, the LNG supply chain can be defined as a combination of two co-dependent values, mainly availability of the infrastructure and fleet and vessel routes. Routes represent the distance which LNG tanker vessels must cover to ensure that all demand for LNG is satisfied. The distance which an LNG bunker vessel must cover to supply fuel to LNG-powered vessels can be determined based on the following  $f(d_{i,k,u})$  function:

$$f(d_{i,k,u}) = \sum_{i=1}^I \sum_{k=1}^K d(J_{u^i}^i, (J+1)_1^i) + d(M_i, J_u^i) + \dots + d((J+1)_1^i, M_i) \quad (1)$$

where:

$d(J_{u^i}^i, (J+1)_1^i)$ —distance covered by an LNG bunker vessel between consecutive LNG-powered vessels represented in the chromosome by genes  $J_{u^i}^i, (J+1)_1^i$ ;

$d(M_i, J_u^i)$ —distance covered by an LNG bunker vessel between an LNG storage facility and an LNG-powered vessel represented in the chromosome by gene  $J_u^i$ ;  
 $d((J+1)_1^i, M_i)$ —distance covered by an LNG bunker vessel between an LNG-powered vessel, represented in the chromosome by gene  $(J+1)_1^i$ , and an LNG storage facility.

The maximum cost coefficient ( $C_{max}$ ) at the transformation of the cost function into the fitness function can be chosen using one of the following four methods:

- It can be read from input;
- It can equal the maximum value encountered so far;
- It can equal the maximum  $k$  value encountered in the recent populations;
- It can fluctuate relative to the variance of the population under analysis.

Then, in the applications of the profit function, the function takes the following form:

$$f(x) = \begin{cases} C_{max} - g(x), & \text{if } g(x) < C_{max} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

With negative values, the utility function appears, whose fitness function takes the following direction:

$$f(x) = \begin{cases} u(x) + C_{min}, & \text{if } u(x) + C_{min} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

The maximum cost coefficient ( $C_{min}$ ) can also be chosen using one of the following four methods:

- It can be read from input;
- It can equal the minimum value encountered so far;
- It can equal the minimum  $k$  value encountered in the recent populations;
- It can fluctuate relative to the variance of the population under analysis.

In order to determine the annual net gain on investment, apart from the capital expenditure of a given LNG port, the LNG unit price which should be offered to end users must be specified. The rate of return can be calculated by the discount method applied in the analysis of investment projects, i.e., the net present value (NPV). In a detailed cost assessment of LNG distribution, the NPV is considered a financial ratio and is used in the assessment of profitability of an investment project. Financial effectiveness is characterised by high sensitivity to changes in particular factors, including, without limitation, price, sales figures, and capital expenditure. The distance which an LNG bunker vessel must cover to supply LNG-powered vessels, on the other hand, has little impact on the NPV.

#### 4. Results

Based on the information above, a model was built in Matlab R2019a software, using genetic algorithms. The southern part of the Baltic Sea was selected as the sample area under analysis. The model's input are statistical data on the number of seagoing vessels calling at ports along the coast. The data, comprising data on vessel traffic from the IALA IWRAP Mk2 system and the Statistical Office in Szczecin for the years 2016–2022, were classified by type of vessel. Based on an analysis of the number of vessels entering particular ports, it was established that LNG facilities should be located in five ports: Świnoujście, Darłowo, Kołobrzeg, Gdynia, and Krynica Morska. The model was verified based on genetic algorithms for 35 LNG bunker vessels and 115 LNG-powered vessels. The bunker vessels represent the existing LNG fleet, and they all have different specifications, since sister vessels were discarded. The number of LNG-powered vessels calling at ports in the Baltic Sea was determined based on the percentage share of particular LNG-powered vessel types in the global fleet. The original model which was created analyses LNG distribution in terms of the duration of the LNG bunkering service, the distance covered by an LNG bunker vessel, the number of LNG bunker vessels and LNG-powered vessels, and cost optimisation.

A simulation was performed for each port in the sample, i.e., the user can choose the port to be analysed. The model is universal, meaning that the user can modify the number of LNG bunker vessels, the probability of mutation, number of iterations, and number of tasks to be performed.

For the considered task of optimising the distribution of LNG (finding the minimum value), the objective function  $f(x)$  is defined. Thanks to its determination, it is possible to numerically assess the adaptation of individual elements (chromosomes) in the population under study, where  $f(x)$  is defined on a set of  $f(x) \rightarrow MIN$ .

$$f(x) = \sum_{a=1}^{NU} \sum_{b=1}^{NB_v} tb_{a,u} * cb_{a,b} + t_{a,b} * ct_{ab} + p \rightarrow MIN \quad (4)$$

where:

$NU$ —number of LNG-fuelled units;

$NB_v$ —number of LNG bunkering vessels;

$tb_{a,b}$ —the LNG bunkering time of the  $j$ th LNG-fuelled vessel;

$t_{a,b}$ —arrival time of the LNG bunker to the LNG-fuelled vessel;

$cb_{a,b}$ —unit hourly cost of LNG bunkering operation;

$ct_{a,b}$ —unit hourly cost of the LNG bunker being en route;

$p$ —fixed cost.

For the purpose of the analysis, a fitness function was developed, representing the cost coefficient for the service of covering the demand for LNG in the Baltic Sea. The simulations were developed for the objective function to provide solutions characterised by the smallest possible cost of LNG distribution. The optimal solution was obtained using genetic algorithms with a suitable coding system, summarised as follows:

- The chromosome structure: genes represent LNG bunker vessels in a 1:1 proportion;
- The parent population is selected based on weights determined on the basis of the previous iteration  $i^{-1}$ ;
- One-point crossover operation; i.e., the crossover point is randomly selected;
- The mutation is performed with a probability of 0.1.

Simulations using genetic algorithms are performed as follows:

1. The population of LNG bunker vessels for a particular port is selected from a pool of 60 LNG bunker vessels.
2. Sets of LNG bunker vessels perform a number of tasks, where the objective function value is determined for each task.
3. The objective functions for each task are summed up and represented by points on a chart. The points show the real demand for LNG from a predetermined group of LNG-powered vessels.
4. The position of an LNG-powered vessel is randomly selected within the limit of operation of the specified LNG facility. This stage constitutes the basis for the solution—specification of a set of LNG bunker vessels for a given port.
5. The objective function value is determined based on the specified LNG bunkering duration, the time the bunker vessel needs to reach the vessel requesting bunkers, and the cost of the LNG bunker vessel's stay in the port (according to the simulation conditions).

Results of a simulation for the port of Świnoujście are shown in Table 3. The obtained solution is the most cost-effective and includes the following:

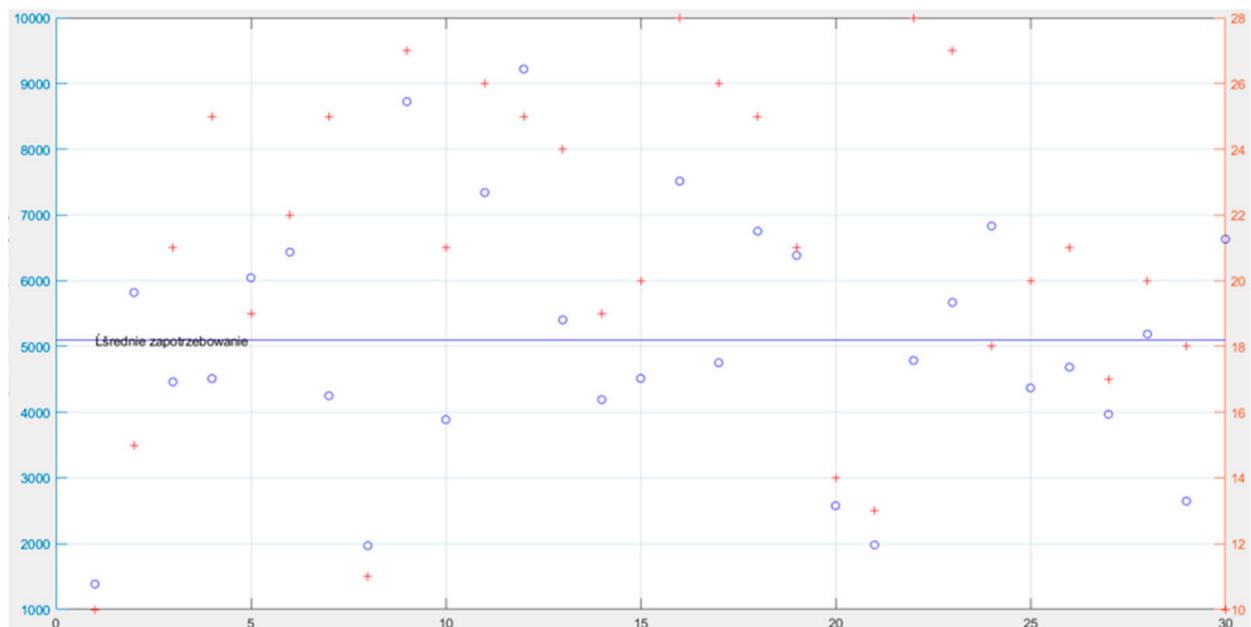
- The time limit necessary for task completion;
- The distance covered by the LNG bunker vessel;
- The demand for LNG.

**Table 3.** Example simulation results for a selected port.

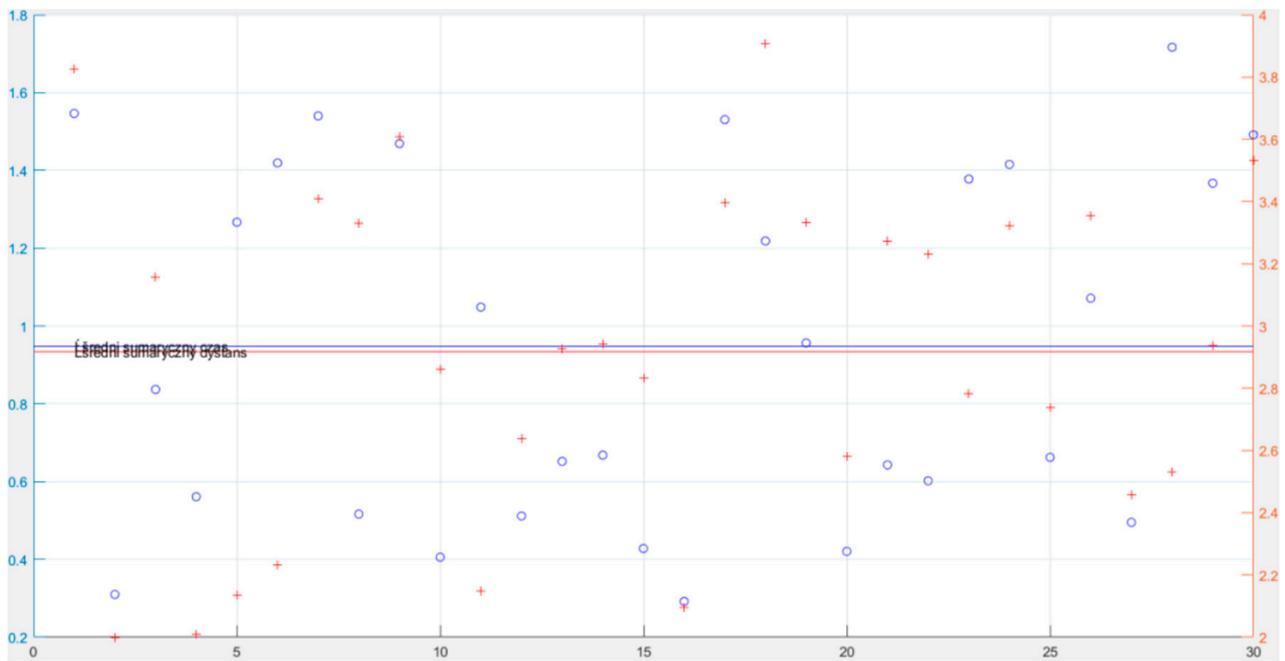
	Name	LNG Carrying Capacity	LOA	Breadth	Service Speed	Loading Rate
	SM JEJU	7501	96.96	21.8	13	1200
	LNG1	6469	119.94	19.4	10	1200
	CARDISSA	2488	88.8	15.3	14.9	500
	MARU	2200	64.62	14.79	8	500
	CLEAN JACK-SONVILLE					
Average time limit for task completion	7	Average distance covered	44	Average demand for LNG		5089

The solution, apart from being displayed in the main application window, facilitates verification based on four charts. The solution defines specifications of the LNG bunker vessels—the vessel's name and technical parameters, such as the LNG tank volume, length overall (LOA), breadth, service speed, and loading rate. The graphical representation includes the following:

1. A chart representing the number of LNG-powered vessels and their demand for fuel (Figure 5);

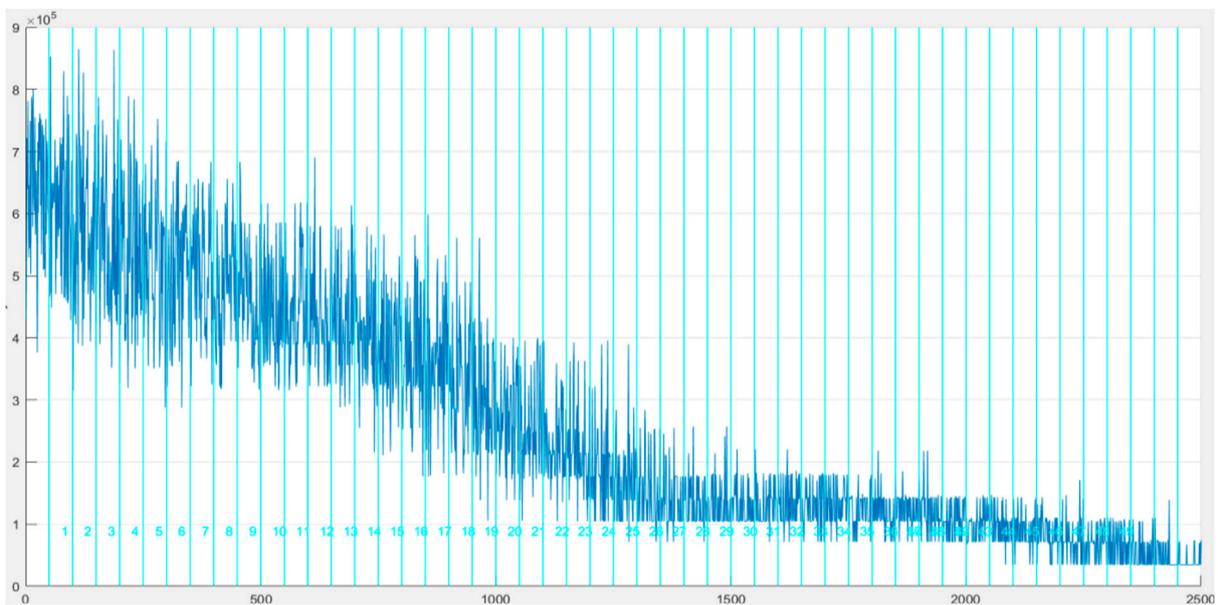
**Figure 5.** Example representation of simulation results.

2. A chart representing the LNG bunkering service (Figure 6);



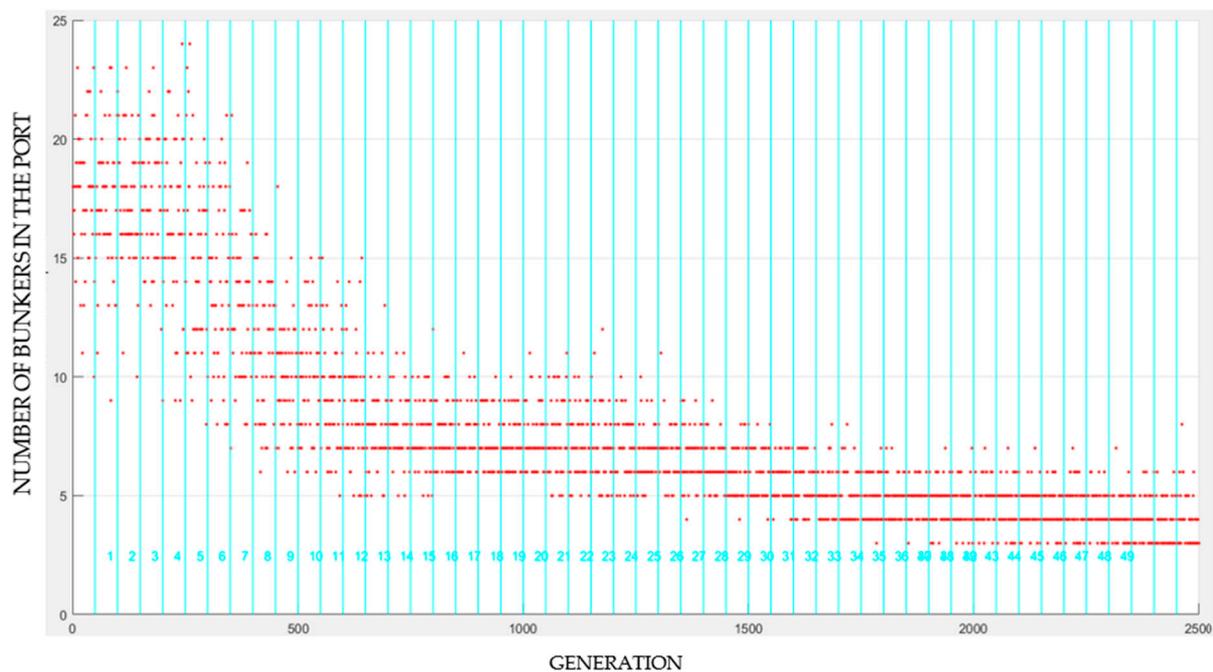
**Figure 6.** Example representation of simulation results.

3. A chart representing the objective function value in consecutive generations of the genetic algorithm (Figure 7);



**Figure 7.** Example representation of simulation results.

4. A chart representing the number of LNG bunker vessels (Figure 8).



**Figure 8.** Example representation of simulation results.

Simulations were performed for each port. An analysis of the results leads to the following conclusions:

1. A simulation generates divergent initial indications of the objective function, resulting from the properties of genetic algorithms. The solution is generated randomly, and the decreasing objective function indicates that the best solution has been generated. Spikes in the objective function value show that accidental mutation has occurred. It means that the function keeps looking for the best solution but cannot find one. Repeated values of the objective function mean that the best solution has been generated.
2. It follows from the principle of the genetic algorithm that the first-generation population is created randomly, and subsequent population iterations are based on individuals from the  $n-1$  population. The generated solutions have a consecutively smaller value of the objective function, which means that a given individual is more likely to reproduce and the probability of obtaining the optimal solution is greater.
3. Values of the objective function in subsequent iterations converge to the desired optimal value, which means that the right algorithm has been chosen to solve the problem of LNG distribution.

A number of simulations were performed to obtain the optimal solution. The results are presented by the best fitted individuals; the optimal solutions correspond to the specified objective function values. One of the properties of stochastic global search algorithms (which include genetic algorithms) is that in each repeated analysis, individuals within a given population explore the search space in a different direction. A detailed analysis of the objective function solutions showed that further simulations were pointless, since they did not generate solutions of a structure corresponding to the unfit region of the search space. Therefore, the smallest value of the simulation is considered to be the optimal solution, taking into consideration the adopted limitations. The optimal solution selected from all the solutions obtained indicates the maximum average demand for LNG from LNG-powered vessels (Table 4). The divergence in results is strictly related to the fact that the applied genetic algorithm is searching for a local rather than a global minimum. In the task under analysis, the best solution is indicated by repeatability of the number of ones. The changing decimals do not affect changes to the algorithm which would affect the final

result of the simulation. Therefore, the solution of the smallest value was adopted as the optimal one. Taking into consideration the principle of operation of genetic algorithms, based on multicriteria optimisation, it is concluded that further simulations for the defined objective function will not generate a solution to improve the final result. The solutions of the applied optimisation in the simulation, admissible and acceptable in view of the concept of the task solution according to the defined criteria, are shown in Table 4.

**Table 4.** Optimal solutions for particular ports.

Port Name	Objective Function (OF) Value	Maximum Average Demand for LNG [m <sup>3</sup> ]
Świnoujście	minOF = $1.1597 \times 10^3$	5692
Darłowo	minOF = $1.1124 \times 10^3$	107
Kołobrzeg	minOF = $1.2964 \times 10^3$	480
Gdynia	minOF = $1.0951 \times 10^3$	35,410
Krynica Morska	minOF = $1.0222 \times 10^3$	292

Taking into consideration repeatability of the results, the obtained values of average demand for LNG should be used in further research aimed at determining the size of LNG distribution facilities. Therefore, the solution of the task can be interpreted as follows:

- For the current number of seagoing vessels sailing in the southern part of the Baltic Sea, the optimal solution is to locate LNG distribution facilities in five ports of Świnoujście, Gdynia, Darłowo, Kołobrzeg, and Krynica Morska;
- Recovery of the cost of construction of LNG storage and bunkering facilities at the ports mentioned above is possible at a mark-up of 50% (a 15-year amortisation period, increased by interest);
- The smallest LNG bunker vessel with a carrying capacity of  $\leq 1000$  m<sup>3</sup> in service at an LNG facility will be able to supply 50,000 m<sup>3</sup> of fuel per year to LNG-powered vessels. The characteristics of the LNG bunker vessel are as follows:
  - a. It will be loaded once a week;
  - b. Supplying fuel to LNG-powered vessels, the LNG bunker vessel will be unloaded within one week;
  - c. The life cycle of the LNG bunker vessel is 20 years;
  - d. The costs of construction:
    - i. 800 m<sup>3</sup> LNG bunker vessel—ca. EUR 12 m;
    - ii. 1200 m<sup>3</sup> LNG bunker vessel—ca. EUR 15 m;

Taking into consideration the following:

- a. Investment costs;
- b. Annual volume of bunkering;
- c. EUR 25/m<sup>3</sup> cost recovery;

The return on investment will be realised over a period of ca. 15 years.

In order to verify correctness of the specified number of vessels entering the ports in the years 2020–2022, a detailed data categorisation was performed and a model of distribution of the number of vessels entering particular ports in a given day was developed. Having performed a test of normality of distribution of the frequency of port entries, it was verified that the sample size criterion ( $N < 100$ ) was met. Next, the distribution was examined using the Shapiro–Wilk test with the adopted significance level of  $\alpha = 0.05$  (Table 5), with the following hypotheses:

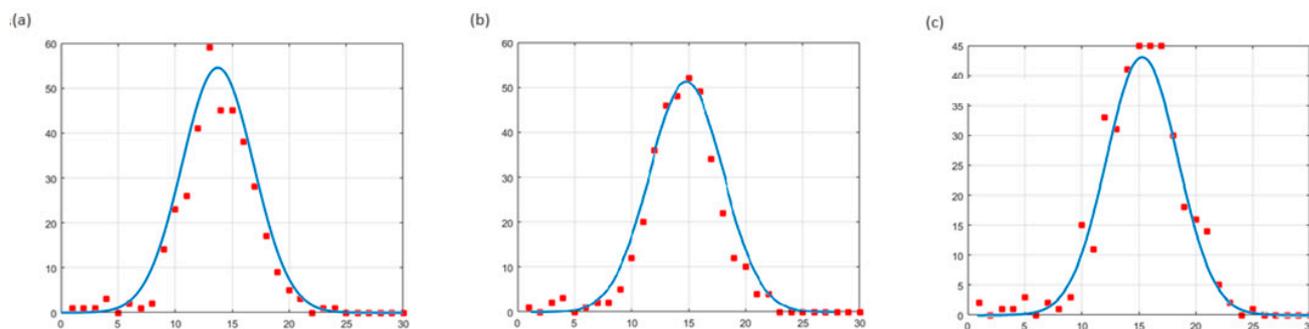
1.  $H_0$ : The distribution of the trait under analysis is a normal distribution;
2.  $H_1$ : The distribution of the trait under analysis is not a normal distribution.

**Table 5.** The Shapiro–Wilk test for the selected port.

Parameter	2020	2021	2022
Test value	0.978	0.9491	0.9441
Critical value *	0.919	0.969	0.969
Basis to discard $H_0$	-	-	-
	Normal distribution	Normal distribution	Normal distribution

\*, value as per tables ( $N = 30$ ,  $\alpha = 0.05$ ).

In further analysis, a normal distribution (blue line) was fitted to the occurrences of the frequency of port entries and it was noted that the expected value and standard deviation could be determined (red bullets). The distribution around the expected value is represented in Figure 9.

**Figure 9.** Fitting of the normal distribution to the number of occurrences of entries to a selected port in the years 2020 (a), 2021 (b), and 2022 (c).

The distribution test was an important part of the analysis. The distribution was found to be normal, which proved that there was a possibility of creating a task-generating model for the optimisation algorithm. It is concluded by inference that having determined the distribution of the entries of vessels to particular ports around the expected value, it is possible to generate a solution to the task which will correspond to real-life circumstances.

## 5. Conclusions

In order to comply with the regulations of the International Maritime Organisation, as of 1 January 2020, environmental targets for emissions reduction have been introduced, requiring shipowners to change vessels' fuel systems and the fuel used in their fleets. The choice of marine fuel has now become an important investment decision.

With an improved energy efficiency index for newly designed vessels, the use of LNG as fuel is expected to help meet the IMO's decarbonisation target for new ships. Considering the control of emissions and the price of LNG, LNG is considered an alternative fuel for all transport modes, especially land and sea transport. The shipping industry is still at the stage of considering the switch from conventional fuels to LNG. Once it happens, the sector will have crossed a milestone towards reducing operating costs and the environmental impact. LNG is a truly environmentally friendly fuel which helps minimise all major emissions, generates lower operating costs, and offers improved performance.

Owing to its higher efficiency and reduced environmental impact, it is the preferred fuel of the future in many industry sectors. With increased processing, storage, and transport of LNG across the world, year on year, the fuel gains importance in the global energy consumption structure. The global demand for LNG as a source of energy is growing rapidly. A well-functioning LNG distribution system requires an adequate number of facilities (such as LNG storage and processing terminals) and an ample LNG fleet (LNG bunker vessels). Considering the constant growth in the number of LNG-fuelled ships, the need for infrastructure and means of transport to cover the bunkering needs has emerged, especially in areas under strict control of sulphur emissions. A well-functioning

infrastructure of fixed LNG facilities and LNG bunker vessels will ensure continuity of supplies.

Genetic algorithms were chosen to build a model for the defined problem. At the very outset, the correctness of their use was assumed. This is because the use of simple optimisation algorithms due to the complexity of the problem could not be implemented.

Genetic algorithms are used in many fields. They also found application in the present work, where they made it possible to solve the optimisation problem with a short duration of analysis and presentation of the solution to the task. Due to the large number of data subjected to analysis, the solution time of the problem plays a special role. Classical optimisation methods used to solve the problem of locating routes do not guarantee the indication of a solution with little time. For this reason, they were not selected in the modelling process.

From the point of view of the difficulty of the problem to be solved due to the constraints involved, the problem is very complicated and a simple model cannot be used. For the defined research problem, there is a very large number of possible solutions, where searching the entire space of them is very time-consuming or unrealistic.

This means that the availability ranges of LNG bunkers can be in infinitely many locations of infinite size. LNG storage facilities can be located in infinitely many locations and LNG bunkers of infinite size can supply LNG-fuelled vessels with fuel in infinitely many locations. Therefore, there are very many solutions. This paper uses a simplification of the problem to fit the model. The problem defined in this way does not find an optimal solution but a quasi-optimal solution (close to or almost equal to the optimal solution).

In view of the above, the authors undertook research aimed at building an LNG distribution model for the southern part of the Baltic Sea. The research is based on the heuristic approach, where the entire search space of various solutions to the specified problem is explored in order to find the optimal one. Considering the complexity of the problem and potential solutions to it, genetic algorithms, inspired by biological evolution of genetic organisms, were used in the research. When solving a problem with genetic algorithms, changes can be introduced at any stage of the process without the necessity of modifying the initially defined task. A universal application was developed in Matlab R2019a software, which:

- Imitates conditions which may correspond to a real-life situation;
- Provides for modifying the input for the analysis, such as:
  - Area;
  - Fuel;
  - Type of vessel (e.g., inclusion of river-going vessels);
  - Technical parameters of the LNG fleet;
  - Vessel traffic density;
  - Technical failures of the LNG fleet;
  - Costs (inclusion of additional costs which may be generated at various stages of the LNG distribution);
  - Meteorological conditions and sea state.

The task of LNG distribution under analysis, comprising the determination of demand for LNG, fleet size, and location of distribution facilities which will satisfy the demand in the specified area, can be modified by the user. The following task components can be modified:

- Location of ports along the southern coast of the Baltic Sea (33 sea ports have been entered);
- Range of distribution (areas of 20 Nm, 30 Nm, and 50 Nm have been entered);
- Technical parameters of LNG bunker vessels (35 types of LNG bunker vessels have been entered);
- Technical parameters of LNG-powered vessels (115 vessels have been entered); the most important is the option of adjusting:
  - The carrying capacity of LNG-powered vessels;

- The probability of bunkering of an LNG-powered vessel.

The solution to the task of cost optimisation which has been generated, characterised by the smallest (best) value of the objective function, specifies:

- Demand for LNG [m<sup>3</sup>];
- Number of LNG bunker vessels and their technical parameters, including the capacity of the LNG tank;
- Number and size of LNG-powered vessels;
- The following bunkering service parameters:
  - Distance covered by the LNG bunker vessel;
  - Time necessary to provide the bunkering service.

A distribution test was performed for the obtained solutions, using the Shapiro–Wilk test with the adopted significance level of  $\alpha = 0.05$ . Having conducted a detailed analysis of the obtained set of simulations performed in an application developed in the Matlab Mk2 environment using genetic algorithms for the southern part of the Baltic Sea, it is inferred that this original application is suitable for use in further research into optimisation solutions for various sea areas. Universality of the developed model has been proven.

To sum up, owing to the fact that LNG generates lower operating and maintenance costs as well as lower emissions of toxic substances into the air, it is a preferred alternative fuel in the shipping industry. Despite obstacles, such as high initial investment costs and complexity of reconfiguration of a fuel system to an LNG-powered system, the number of LNG-powered vessels is on a constant upward trend. LNG-powered vessels are characterised by improved economic effectiveness measured by the return on equity (ROE) and life cycle cost, where vessel mileage, fuel price, lifetime, and the LNG fuel system are parameters subject to change.

Owing to its higher efficiency and reduced environmental impact, LNG is the preferred fuel of the future in many industry sectors. It has led to increased processing, storage, and transport of high volumes of LNG across the world. Therefore, there is a need to create infrastructure which can efficiently handle LNG distribution worldwide.

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