

Article

Port Classification for LNG Bunkering Development in the Baltic Sea Transport System

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Abstract

The energy transition in maritime shipping is increasing the importance of alternative fuels and port infrastructure capable of handling them in a safe, regular, and economically justified manner. In this context, LNG remains a transitional fuel with a relatively high level of technological and organizational maturity, particularly in regions characterized by intensive liner, ferry, and RO-RO traffic. This article proposes a universal model for organizing LNG distribution within the port–transport system, based on three interdependent dimensions: demand potential, infrastructure readiness, and operational feasibility. The model structure enables the classification of ports according to their functions within the regional bunkering network and the identification of nodes of the greatest systemic importance. The model was validated using data on vessel calls, the structure of container and RO-RO traffic, LNG infrastructure status, and monthly traffic variability. The analysis demonstrated that the most justified LNG distribution arrangement in the Baltic Sea is polycentric in nature and concentrated in ports, combining a high degree of transport regularity with confirmed LNG readiness. The results indicate that the rationale for LNG infrastructure development is selective in nature and depends on the actual position of a port within the transport network, rather than solely on cargo throughput volume. The proposed model also retains its applicability to other alternative fuels after adjustment of technological, regulatory, and operational parameters. By supporting the selective development of alternative-fuel infrastructure in ports with the highest systemic relevance, the model contributes to sustainable maritime transport planning and to the transition toward lower-emission port–transport systems.

Keywords: maritime sustainability; LNG bunkering; alternative marine fuels; sustainable port infrastructure; port classification; Baltic Sea ports; multicriteria assessment; maritime decarbonization



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1. Introduction

The fuel transition in maritime shipping currently represents one of the principal directions of change in maritime transport. Its importance stems both from increasingly stringent environmental requirements and from the progressive tightening of legal requirements governing ship operations [1,2]. The revised 2023 IMO Strategy sets the course toward achieving net-zero emissions in international shipping by 2050, while FuelEU Maritime and the EU ETS reinforce the role of fuels with lower emission intensity in the operation of vessels calling at ports of the European Union [3,4]. As a consequence, port fuel infrastructure is becoming one of the key factors determining the feasibility of implementing alternative fuels in shipping. From a sustainability perspective, the

location and functional role of alternative-fuel infrastructure in ports are important because they affect the environmental effectiveness, operational reliability, and economic rationality of the maritime energy transition. Selective infrastructure development may reduce the risk of inefficient investments and support a more resilient and lower-emission port–transport system.

Among alternative fuels, LNG occupies a particular position. Its importance results from its relatively high level of technological maturity [5], the availability of bunkering solutions [6,7], and the existing operational base in selected fleet segments [8,9]. At the same time, LNG is not a target fuel from the perspective of the sector’s long-term decarbonization. The literature indicates that its use should be regarded as a transitional solution, the environmental effectiveness of which depends on limiting methane emissions and on the parameters of the entire fuel supply chain [10–13]. Thus, the rationale for analyzing LNG does not arise from its ultimate technological superiority but from the fact that it remains the alternative fuel with the highest degree of operational deployment in maritime shipping.

Previous studies on alternative fuels in shipping have most often focused on the analysis of emission parameters, comparisons of propulsion technologies, assessments of fuel costs, or examinations of individual bunkering infrastructure cases [14–18]. Much less frequently, studies have been undertaken that integrate vessel traffic structure, port function, infrastructure readiness, and the operational conditions for bunkering within a single analytical model. Consequently, a research gap remains visible between the assessment of the fuel itself and the assessment of the port–transport system in which the fuel is to be distributed and used. This gap is particularly relevant for LNG because the feasibility of its use depends not only on fuel properties but also on the spatial configuration of ports, the availability of bunkering infrastructure, the regularity of vessel traffic, and the operational connection between ports and fuel-supply facilities.

The Baltic Sea constitutes an appropriate research area for this type of analysis. This follows from the high intensity of short-sea shipping, the substantial share of RO-RO and ferry transport, the significant concentration of ports with diversified functional profiles, and the application of stringent environmental requirements. At the same time, the region includes container ports, ferry ports, mixed-function ports, and ports linked to gas infrastructure, which makes it possible to analyze the LNG distribution system within a multi-node framework [19,20]. It is also important that the region already includes ports offering LNG bunkering services, port procedures for LNG, or documented bunkering operations, which enable an analysis based on actual operational premises.

This study adopts the assumption that the importance of a port in the LNG distribution system is a function of three groups of factors: demand potential, infrastructure readiness, and operational feasibility. This means that neither cargo throughput volume nor the mere presence of LNG infrastructure can be treated as a decisive criterion. A high cargo volume does not automatically determine a port’s suitability for the LNG system, just as the formal availability of infrastructure does not provide a sufficient basis for assigning a core function to a port if that port does not generate sufficiently regular and stable traffic.

For this reason, a model of a universal character is proposed. The universality of the model means that its structure is based on constant systemic elements, comprising demand, infrastructure, and operational feasibility, rather than on the specificity of a single fuel. As a result, the model may also be applied to other alternative fuels, provided that the relevant technological, safety, fuel cost, and emission cost parameters are adjusted. Such an approach makes it possible to use a uniform analytical framework to compare different variants of fuel system organization in seaports.

In light of the above conditions, the research problem can be reduced to determining how to construct a model that enables the classification of ports from the perspective of their importance to the regional LNG distribution system and what implications for the structure of the port network follow from its application to the Baltic Sea area.

The remainder of the paper is organized as follows: Section 2 presents the model structure, input data, implementation, and validation procedure. Section 3 reports the port-classification results. Section 4 discusses the methodological and practical implications of the findings, together with the study limitations. Section 5 concludes the paper.

2. Materials and Methods

2.1. Structure of the Decision Model

In this study, the organization of LNG distribution within the port–transport system was assumed to constitute a multi-layered problem in which demand-related, spatial, infrastructural, and operational interdependencies occur simultaneously. This means that the significance of a port for the LNG bunkering system cannot be determined solely on the basis of a single characteristic, such as cargo throughput volume, number of vessel calls, or the presence of an LNG terminal. A port may generate substantial vessel traffic while lacking the technical conditions required to perform bunkering operations. Conversely, it may possess LNG infrastructure while failing to generate traffic sufficient to economically justify a fuel-supply function. For this reason, the model was constructed as a framework combining three fundamental components: demand potential, infrastructure readiness, and operational feasibility.

The approach is therefore a multicriteria port-classification model in which ports are assessed and assigned to functional classes rather than optimized as elements of a sailing route, transport schedule, or bunkering sequence. The model is therefore positioned at the strategic planning level. It does not reproduce the full physical LNG supply chain but identifies ports in which LNG bunkering functions are most justified and may be further integrated with storage, terminal, truck-to-ship, or ship-to-ship supply arrangements.

The demand component of the model describes vessel traffic intensity and its structural composition within the port. On this basis, the level of demand for LNG bunkering services is determined. The infrastructure component is used to assess whether the port possesses the technical and organizational conditions required to enter the LNG system. The operational component refers to the ability to perform bunkering services within a specified time, over a defined distribution range, and under the capacity constraints of the servicing units. Such a model structure is consistent with the logic adopted in this study, in which vessel traffic intensity, LNG demand, distribution range, and the selection of ports capable of covering fuel demand were analyzed.

Consequently, the model is intended not merely to compare ports, but to determine their functions within the regional LNG distribution system. This involves the identification of core ports, supporting ports, and ports of local significance. At the same time, the adopted model is universal in character, because, after adjustment of fuel-specific, safety, emission, and cost parameters, it may also be applied to other alternative fuels.

In such an application, the model should be parameterized separately for each fuel type. For a given fuel f , the relevant parameters may include the required safety radius r_f , the required storage and handling area $A_{\text{req},f}$, the energy-density parameter e_f , and the port–fuel compatibility factor h_{pf} . These parameters are particularly important when comparing LNG with methanol or ammonia, because these fuels differ substantially in terms of safety requirements, storage footprint, handling procedures, and regulatory conditions.

A simplified fuel-specific feasibility condition can be expressed as:

$$X_{pf} = \begin{cases} 1, & \text{if } A_p \geq A_{req,f}, B_p \geq r_f, h_{pf} = 1 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where:

X_{pf} — indicates whether port p is feasible for fuel f ,

A_p — denotes the available area in port p ,

$A_{req,f}$ — is the required storage and handling area for fuel f ,

B_p — denotes the available safety buffer in the port, r_f is the required safety radius for fuel f ,

h_{pf} — represents the compatibility of port p with the technical and regulatory requirements of fuel f .

This parameterized structure prevents LNG-specific infrastructure assumptions from being automatically transferred to methanol, ammonia, or other alternative marine fuels.

2.2. Scope of the Study

The first stage of the study involved defining the reference set of ports for the Baltic Sea region. In practice, the number of ports operating in this area depends on the adopted classification criterion, since, alongside major commercial ports, there are also local, passenger, fishing, industrial, and functionally specialized ports. From the perspective of the LNG distribution organization model, however, there is no justification for treating all of these facilities as elements of equal significance. For this reason, the reference set was defined as the 87 seaports of the Baltic Sea region included in the TEN-T network, as these are facilities of confirmed transport importance at the European, national, or regional level [21,22].

Within the TEN-T network, seaports are divided into core ports and comprehensive ports [23,24]. Core ports constitute part of the main transport network of the European Union [25]. These are ports of the highest importance for international cargo and passenger flows, linked to the principal transport corridors and to infrastructure of strategic significance for the functioning of the common market [26,27]. Comprehensive ports, by contrast, belong to the complementary network [28–30]. This means that they also perform a function within the transport system of the European Union; however, their significance is more often regional, national, or subregional in nature [24]. In the context of the present study, this distinction is methodologically important, as it makes it possible to differentiate ports of potentially highest systemic importance from ports performing supporting or local functions [31].

However, membership in the TEN-T network alone does not mean that all ports should be analyzed with the same level of detail. In the LNG distribution organization model, the scope of detailed analysis should be differentiated depending on the transport function of the port, traffic volume, its position in the transport network, and the infrastructural premises related to the handling of alternative fuels. Ports generating low traffic, not participating in the main shipping corridors, and lacking an LNG infrastructure layer do not, in practice, constitute candidates for core functions within the fuel system. Including them in the detailed analysis on the same basis as major ports would lead to excessive dispersion of the model and weaken its interpretative capacity.

For this reason, purposive sampling of the analytical sample was applied in the second stage. Ports were qualified for detailed analysis if they met at least one of three criteria. The first criterion concerned the port's importance within the regional container or RO-RO system, since these transport segments generate the highest level of traffic regularity and the greatest probability of alternative fuel use in liner and ferry shipping. The second criterion referred to the port's location along the main transport corridors of the Baltic Sea.

Ports situated on such corridors have greater potential to perform the function of systemic nodes than peripheral ports or those of exclusively local significance. The third criterion concerned the existence of a publicly confirmed LNG layer, understood as the presence of bunkering services, terminals, operational procedures, or documented LNG operations. This approach made it possible to relate the analysis not only to port traffic but also to the actual capabilities for fuel handling (Table 1).

Table 1. Characteristics of the reference port set and port selection criteria [20,24,32–34].

Category	Characteristics	Relevance to the Model
TEN-T core ports	Ports of the highest importance within the main EU transport network	Potential core ports of the LNG system
TEN-T comprehensive ports	Ports complementing the main network, of regional or national importance	Potential supporting or local ports
Container ports	Ports with a dominant role in liner shipping and containerized cargo handling	High demand potential for the fuel supply system
RO-RO/ferry/RO-PAX ports	Ports serving regular ferry and RO-RO services	High operational predictability and service regularity
Ports with an LNG layer	Ports possessing terminals, LNG services, bunkering procedures, or documented LNG operations	High infrastructure readiness
Local ports with low traffic intensity	Ports with a limited scale of activity and a weak network position	Low suitability for a core function

The reference port set comprises ports of different levels of transport significance and performing different functions within the regional system. Not all ports play the same role from the perspective of LNG distribution organization. Some of them may constitute the basis of the regional bunkering system, some may perform a supporting function, and others remain relevant only at the local scale. This means that the subsequent analysis should not be conducted at the same level of detail for all ports.

2.3. Input Data for the Model

In the LNG distribution model, the scope of detailed analysis was differentiated according to the transport function of the port, traffic volume, and its significance for the potential bunkering network. Such an approach is necessary because the full population of Baltic Sea ports includes both ports of strategic importance and ports whose role in the regional fuel system is limited.

Ports were qualified for detailed analysis if they met at least one of three criteria. The first criterion concerned the port's importance within the regional container or RO-RO system. The second criterion referred to the port's location along the main transport corridors of the Baltic Sea. The third criterion concerned the existence of a publicly confirmed LNG layer, understood as the presence of bunkering services, an LNG terminal, operational procedures, or documented LNG operations.

On this basis, the following ports were selected: Gdańsk, Gdynia, the Szczecin–Świnoujście port complex, Klaipėda, Riga, Tallinn, Helsinki, HaminaKotka, Rostock, and Trelleborg (Table 2). This set includes ports representing the main subregions of the Baltic Sea and the principal functions of the transport system: container shipping, RO-RO and ferry transport, mixed-function ports, and ports with a confirmed LNG layer. This selection makes it possible to analyze the LNG distribution system not as a homogeneous arrange-

ment but as a structure composed of ports with different functional positions and varying operational significance.

Table 2. Ports included in the analysis [24,35–37].

Port	Dominant Traffic Profile	Reason for Inclusion
Gdańsk	container, deep-sea, fuel	the largest container port in the Baltic Sea region, with a publicly announced LNG service
Gdynia	container, RO-RO, short-sea	a mixed-function port of high regional significance
Szczecin–Świnoujście	RO-RO, ferry, bulk	western RO-RO gateway and proximity to an LNG terminal
Klaipėda	container, LNG, RO-RO	confirmed ship-to-ship LNG bunkering
Riga	container, bulk	an important port in the central-eastern part of the Baltic Sea region
Tallinn	RO-RO, RO-PAX, ferry	the main hub of the Gulf of Finland with formal LNG authorization
Helsinki	RO-RO, RO-PAX, ferry, container	very high traffic regularity and developed LNG procedures
HaminaKotka	container, industrial	representation of the north-eastern part of the region
Rostock	RO-RO, ferry	a strong western ferry and freight gateway
Trelleborg	RO-RO, ferry	the largest RO-RO port in the Baltic Sea region

The analytical sample was not limited exclusively to the largest container ports or solely to ports equipped with LNG infrastructure. The applied selection combines three perspectives: traffic intensity and structure, the port's position within the spatial system, and the degree of preparedness for LNG handling. This makes it possible to capture both ports with a clearly defined core function and ports whose role within the system may be supporting or local in nature. In turn, this provides the basis for the further classification of ports at the stage of model results rather than at the level of object selection itself.

In the subsequent part of the model, four groups of input data were used. The first group consisted of the number of vessel calls at the port, treated as the basic measure of the port's operational intensity. For Polish ports, the data source comprised publications of the Central Statistical Office (GUS) on the maritime economy and statistical yearbooks of the maritime economy, whereas for the remaining ports, annual port reports and official statistics published by port authorities were used. The number of vessel calls was adopted as the primary variable because it makes it possible to distinguish between ports handling a large number of regular arrivals and ports achieving high cargo throughput volumes with a relatively small number of large vessels. From the perspective of LNG bunkering organization, these situations have different operational interpretations. In the former case, the predictability of demand for bunkering increases, whereas in the latter case, greater importance may be attached to the one-off scale of demand and the longer service cycle of the vessel.

The second group of data comprised the structure of port traffic, described by container throughput and RO-RO/ferry transport volumes. These variables do not replace the number of vessel calls but serve a complementary function, as they make it possible to identify the dominant functional profile of the port. Container throughput reflects the port's importance in liner and deep-sea shipping, whereas RO-RO/ferry traffic describes the intensity of ferry, RO-PAX, and freight ferry transport. Under Baltic Sea conditions, the latter variable is of particular importance, because regular ferry and RO-RO connections increase the predictability of bunkering services and create a more stable operational rhythm than irregular traffic.

The third group consisted of data relating to LNG readiness. In this part of the model, no declarative expert assessment was applied; instead, measurable premises indicating the port's actual preparedness for LNG handling were used. Indicators of high readiness included a publicly announced LNG bunkering service, an applicable LNG manual or safety procedures, port regulations permitting truck-to-ship or ship-to-ship operations, the presence of an LNG terminal, or confirmed execution of bunkering operations. A variable defined in this way makes it possible to distinguish between ports demonstrating actual preparedness for LNG handling and ports in which such potential remains merely declarative or hypothetical.

The fourth group of data concerned traffic seasonality. This variable was not introduced as a separate component of the ranking, but as an element for interpreting operational conditions. This solution was adopted deliberately because seasonality does not necessarily alter a port's position within the network structure, but it does affect monthly fluctuations in infrastructure load, the availability of bunkering windows, and the intensity of ferry and RO-PAX service utilization. Helsinki was adopted as the reference port because it publishes consistent monthly data on vessel calls, passenger traffic, and cargo traffic, which makes it possible to capture the extent to which seasonal changes in traffic intensity affect the conditions for the provision of bunkering services (Table 3).

Table 3. Input data.

Variable	Analytical Significance	Function in the Model
Number of vessel calls	measure of the port's operational intensity	core of the demand layer
Container throughput [TEU]	indicator of the port's position in liner and deep-sea shipping	complement to the demand layer
RO-RO/ferry throughput	indicator of service regularity and short service cycle	demand–operational layer
LNG status	measure of actual infrastructure readiness	infrastructure layer
Monthly seasonality	effect of temporal variability on service load	interpretation of the operational layer

The application of the above criteria made it possible to avoid restricting the analysis exclusively to the largest and best-equipped ports. The model should also be useful for ports of different scales and functions. In other words, the validity of the model depends on its ability to distinguish between different levels of readiness, rather than merely confirming the advantage of the largest ports.

The model incorporated data describing four basic groups of port characteristics: vessel traffic intensity, the structure of port traffic, the degree of readiness for LNG handling, and traffic seasonality. This selection of data follows directly from the structure of the model. The number of vessel calls constitutes the basic measure of a port's operational intensity and makes it possible to determine whether the port generates traffic on a scale sufficient to support the development of an LNG bunkering function. The structure of port traffic enables the distinction between predominantly container ports, RO-RO/ferry ports, mixed-function ports, and ports with a clearly defined bulk or energy-related function. The variable describing LNG readiness was defined on the basis of verifiable premises, such as the presence of a terminal, bunkering services, formal procedures, or confirmed bunkering operations. Traffic seasonality was treated as an interpretative variable for the operational part of the model, because it does not automatically change the position of a port within the network structure, but it does affect the monthly load on infrastructure and the availability of bunkering windows. Data for Polish ports were based on maritime

economy statistics, while data for foreign ports were derived from annual port reports, official statistics published by port authorities, and port operational documents (Table 4).

Table 4. Input data for the ports included in the analysis [35,37–39].

Port	Vessel Calls/Traffic Intensity	Port Traffic Structure	Annotation on LNG Readiness	Traffic Seasonality
Gdańsk	4215 cargo vessel calls (2024)	container, fuel, and deep-sea port; 2,248,764 TEU in 2024	publicly announced LNG bunkering service	low to moderate; predominance of cargo traffic
Gdynia	3758 cargo vessel calls (2024)	mixed-function port; 974,586 TEU and 201,566 RO-RO units in 2024	development potential, but without an LNG layer as strongly confirmed as in Gdańsk	moderate
Szczecin	2970 cargo vessel calls (2024)	bulk and general cargo port	hinterland of the port complex associated with LNG infrastructure	moderate
Świnoujście	6420 cargo vessel calls (2024)	RO-RO/ferry and bulk port; 468,346 RO-RO units in the port complex in 2024	direct connection to the LNG terminal, with quays having bunkering potential	moderate to high
Klaipėda	5478 vessel calls (2024)	container and RO-RO port; 1,068,771 TEU and 336,792 RO-RO units in 2024	confirmed ship-to-ship LNG bunkering	moderate
Riga	2494 vessel calls (2024)	mixed-function port; containerized cargo accounted for 28% of total port throughput in 2024	no strongly confirmed LNG layer in publicly available port data	low to moderate
Tallinn	7127 vessel calls (2024)	RO-RO, RO-PAX, and ferry port; 565,192 RO-RO units in 2024	formal authorization for LNG TTS/STS operations and ongoing LNG infrastructure development	high
Helsinki	7293 international vessel calls (2025)	RO-RO, RO-PAX, ferry, and container port; 486,000 TEU and more than 640,000 heavy road units in 2025	port LNG manual and bunkering safety procedures	high
HaminaKotka	1749 vessel calls (2025); year-round industrial traffic	container and industrial port; 515,815 TEU in 2025	limited publicly confirmed LNG layer	low to moderate
Rostock	7580 vessel calls (2024)	RO-RO/ferry and cargo port; 5857 ferry and RO-RO vessel calls in 2024	the port permits LNG bunkering, has relevant procedures, and carried out its first STS LNG bunkering operation as early as 2020	moderate to high
Trelleborg	approx. 28 arrivals/departures daily (2024); port with very high ferry/RO-RO traffic frequency	ferry/RO-RO port	LNG port regulations in place, infrastructure being adapted for LNG-fueled vessels; no LNG layer as strongly confirmed as in core ports	high

Note: The reference years correspond to the most recent official annual public data available for each port at the time the model was developed. For Trelleborg, the port authority publishes daily ferry and RO-RO traffic intensity as an operational indicator; therefore, this parameter was used in the table instead of the annual number of vessel calls reported in a uniform statistical format.

Ports with clearly differentiated traffic profiles were included in the model. Gdańsk and Klaipėda primarily represent container ports of major importance for liner shipping, whereas Tallinn, Helsinki, Trelleborg, and Rostock are ports strongly associated with RO-RO, ferry, and RO-PAX traffic. The Szczecin–Świnoujście port complex has a mixed profile, but with a highly significant ferry and RO-RO function as well as a direct connection to LNG infrastructure. Gdynia, Riga, and HaminaKotka, in turn, represent ports with mixed or industrial–container traffic profiles, whose position within the LNG system requires further comparative assessment. Such differentiation of the sample is of fundamental importance because the model is not intended to confirm the advantage of the largest ports but rather to

distinguish between ports with different traffic structures and different degrees of readiness to enter the LNG bunkering system. For this reason, the input dataset simultaneously includes vessel calls, traffic structure, LNG annotation, and seasonality. This makes it possible to move from a simple description of ports to their functional classification within the regional fuel distribution system.

2.4. Model Implementation and Classification Procedure

The proposed approach is a multicriteria port-classification framework supported by a genetic algorithm. The model is not intended to optimize vessel routes or bunkering schedules. Its purpose is to assign ports to functional classes within the regional LNG distribution system on the basis of demand potential, infrastructure readiness, and operational feasibility. Since the classification depends on multiple discrete variables, spatial relations, and operational constraints, a heuristic procedure is used to explore alternative port-classification configurations [40,41].

The procedure consisted of four steps: first, input data on vessel traffic, traffic structure, LNG readiness, and seasonality were collected and standardized; second, the demand, infrastructure, and operational indicators were calculated; third, these indicators were combined into the synthetic port indicator W_p ; and fourth, ports were assigned to the local, supporting, or core class using the genetic algorithm. The standardization step was necessary because the input variables were heterogeneous and expressed in different units, including vessel calls, container throughput, RO-RO/ferry volumes, LNG readiness, and seasonality. Quantitative variables were transformed into a common comparative scale in order to prevent variables with larger numerical ranges from dominating the synthetic indicator. Qualitative variables, especially LNG readiness, were coded on the basis of verifiable premises, such as the presence of LNG infrastructure, bunkering procedures, LNG services, or confirmed bunkering operations. The model outputs are the synthetic port indicator W_p and the final functional class assigned to each port: local, supporting, or core.

The model was implemented in the Python 3.12 environment. The libraries pandas, numpy, and scikit-learn were used for data preparation and standardization; GeoPandas and QGIS 3.34 were applied for spatial analysis; and the DEAP library was used to implement the heuristic procedure. This set of tools was selected because it enables the integration of tabular data, spatial data, and an optimization algorithm within a single reproducible computational environment. In the context of the present study, this was of particular importance because port classification results not only from the values of input variables but also from their mutual spatial and functional relationships.

A genetic algorithm was used as a supporting classification procedure rather than as a routing or scheduling optimizer. The choice of this method follows from the nature of the analyzed problem, which takes the form of a classification–allocation task [42–45]. Ports are assigned to functional classes, and the quality of the solution depends simultaneously on the demand, infrastructure, and operational components, as well as on the spatial distribution of ports. Such a problem has no simple linear form, and its solution space is extensive and discontinuous. The use of a genetic algorithm therefore makes it possible to search a large set of feasible configurations and to select high-quality solutions [46–48].

The genetic algorithm was applied not because of the large size of the port sample, but because of the classification–allocation nature of the problem. Even for a limited purposive sample, the task does not consist of ranking ports by a single variable. Each port may be assigned to one of three functional classes, while the quality of the entire solution depends on demand, infrastructure, operational feasibility, and the spatial distribution of core ports.

The algorithm was therefore used as a supporting procedure to test alternative classification configurations and assess the stability of the results.

The adopted weights reflect the functional logic of the LNG bunkering system. The highest weight was assigned to demand, because without stable vessel traffic, the development of bunkering is not justified. Infrastructure received the second-highest weight, because it determines whether bunkering is technically and organizationally feasible. The operational component was assigned a lower but still relevant weight, as it corrects the result by indicating whether the service can be maintained under real port conditions. To reduce the subjectivity of this choice, several weight variants were tested, and the baseline variant was adopted only after sensitivity validation.

In the model, integer encoding was adopted because the problem is multidimensional [49,50]. Each port may be assigned to one of three classes: core, supporting, or local. The chromosome was defined as a vector whose length is equal to the number of ports included in the detailed analysis, and each gene assumed one of three values:

- 0—local port,
- 1—supporting port,
- 2—core port.

This encoding scheme was considered more appropriate than binary encoding, which would be suitable only for a two-state problem, and more appropriate than permutation encoding, which is used primarily in sequencing and routing problems. In the present case, the solution does not consist of determining the order in which ports are visited, but of assigning to each port a single function within the regional LNG distribution system.

In the computational procedure, tournament selection, one-point crossover, and mutation with a low probability were applied. Tournament selection made it possible to prefer higher-quality solutions while maintaining population diversity [51]. One-point crossover enabled the exchange of chromosome fragments between individuals, whereas mutation counteracted premature algorithm convergence [52,53]. In addition, elitism was applied so that the highest-quality solutions were preserved in subsequent generations.

Each individual in the population represented one feasible variant of the organization of the regional port system. Solution quality in the genetic algorithm was assessed at the configuration level. The port-level synthetic indicator W_p was used to evaluate the systemic importance of individual ports, while an additional configuration quality score $Q(c)$ was applied to account for the spatial distribution of ports classified as core ports. As a result, the model did not merely identify individually strong ports, but rather such a configuration of ports that preserves network logic at the scale of the entire sea basin.

In order to ensure comparability between ports and to link the descriptive part with the optimization procedure, three partial indicators and one synthetic indicator were applied. The partial indicators correspond to the three basic components of the model: demand, infrastructure, and operation. The synthetic indicator serves to determine the functional position of a port within the regional LNG distribution system.

The demand indicator describes the intensity and structure of port traffic. It was assumed that its value depends on the number of vessel calls, container throughput, and RO-RO/ferry throughput. The demand indicator was not interpreted as a simple count of vessel calls. Instead, vessel calls were combined with traffic-structure variables in order to distinguish between ports with frequent calls of smaller vessels and ports with fewer calls but higher potential fuel demand generated by larger vessel segments. In this formulation, container throughput and RO-RO/ferry throughput serve as structural proxies for the scale and regularity of demand. Formally, this indicator was expressed as follows:

$$D_p = \omega_v V_p + \omega_c C_p + \omega_r R_p \quad (2)$$

where:

D_p —denotes the port demand indicator,
 V_p —standardized number of vessel calls,
 C_p —standardized container-throughput component,
 R_p —standardized RO-RO/ferry-throughput component,
 $\omega_v, \omega_c, \omega_r$ —weights assigned to the demand variables, with $\omega_v + \omega_c + \omega_r = 1$.

For applications in which detailed vessel-class data are available, the demand component may be further specified as:

$$D_p^* = \sum_{k=1}^K N_{pk} q_k \quad (3)$$

where:

N_{pk} —denotes the number of calls at port p by vessels belonging to class k ,
 q_k —represents the estimated fuel or energy demand per call for vessel class k ,
 K —the number of vessel classes.

This extended formulation makes it possible to assign a higher demand value to a port with fewer ultra-large vessel calls if the estimated fuel demand per call is substantially higher than in the case of smaller vessels.

The infrastructure indicator describes the actual level of a port's preparedness for LNG handling. It accounts for the presence of an LNG bunkering service, an LNG terminal or fuel supply infrastructure, as well as formal procedures or completed bunkering operations. This indicator took the following form:

$$I_p = \beta_1 U_p + \beta_2 T_p + \beta_3 B_p \quad (4)$$

where:

I_p —port infrastructure indicator p ,
 U_p —presence of an LNG service,
 T_p —presence of an LNG terminal or fuel supply infrastructure,
 B_p —presence of procedures or completed bunkering operations,
 $\beta_1, \beta_2, \beta_3$ —weights of the infrastructure component variables.

The operational indicator describes the practical feasibility of carrying out bunkering under port and regional conditions. It accounts for traffic regularity, the port's position within the spatial system, and the operational conditions for service provision. This indicator was defined as follows:

$$O_p = \gamma_1 S_p + \gamma_2 A_p + \gamma_3 E_p \quad (5)$$

where:

O_p —port operational indicator p ,
 S_p —traffic regularity,
 A_p —spatial accessibility and the port's position in the network,
 E_p —operational conditions for bunkering,
 $\gamma_1, \gamma_2, \gamma_3$ —weights of the operational component variables.

Based on the three partial indicators, a synthetic indicator was calculated:

$$W_p = \delta_1 D_p + \delta_2 I_p + \delta_3 O_p \quad (6)$$

subject to the following constraint:

$$\delta_1 + \delta_2 + \delta_3 = 1 \quad (7)$$

where:

W_p —synthetic port indicator p ,

$\delta_1, \delta_2, \delta_3$ —weights assigned to the demand, infrastructure, and operational components, respectively.

The synthetic indicator W_p evaluates the systemic importance of an individual port. However, the genetic algorithm evaluates an entire port-classification configuration rather than isolated ports. Therefore, an additional configuration quality score was introduced to connect the port-level synthetic indicator with the spatial structure of the solution.

$$Q(c) = \frac{1}{m} \sum_{p=1}^n 1(c_p = 2) W_p - \lambda_{conc} P_{conc}(c) \quad (8)$$

where:

$Q(c)$ —denotes the quality score of the port-classification configuration,

$c = (c_1, c_2, \dots, c_n)$ —chromosome representing the assignment of ports to functional classes

$c_p = 0$ —denotes a local port,

$c_p = 1$ —denotes a supporting port,

$c_p = 2$ —denotes a core port.

W_p —synthetic indicator of port p ,

$m = \sum_{p=1}^n 1(c_p = 2)$ —number of ports classified as core ports,

λ_{conc} —is the weight assigned to this penalty,

$P_{conc}(c)$ —concentration penalty.

The first term rewards configurations in which ports classified as core ports have high synthetic indicator values, whereas the second term reduces the score when core ports are excessively concentrated in space.

$$P_{conc}(c) = \frac{2}{m(m-1)} \sum_{p=1}^n \sum_{q=p+1}^n 1(c_p = 2) 1(c_q = 2) \max(0, \frac{d_{min} - d_{pq}}{d_{min}}) \quad (9)$$

for $m \geq 2$. If $m < 2$, then $P_{conc}(c) = 0$

In this expression, d_{pq} denotes the distance between ports p and q , while d_{min} denotes the minimum desired distance between core ports. The penalty is equal to zero when the distance between a pair of core ports is greater than or equal to d_{min} , and it increases when the ports are located closer than the adopted minimum threshold.

The following sets were analyzed:

- (0.45, 0.35, 0.20),
- (0.40, 0.40, 0.20),
- (0.50, 0.30, 0.20),
- (0.40, 0.30, 0.30).

The selection of these variants resulted from the need to examine how port classification changes when the relative importance of the demand component, infrastructure, and operational feasibility is shifted. The baseline variant assumed the highest weight for the demand component, the second-highest weight for the infrastructure component, and the third-highest weight for the operational component. The remaining variants were tested in order to determine whether the solution was not excessively dependent on the dominance of a single component of the model. In the second stage, 100 independent runs

of the genetic algorithm were performed for each weight variant. The number of 100 was adopted as a compromise between estimation stability and computational cost. In the case of stochastic methods, a single run cannot be regarded as a sufficient basis for inference, because the result depends on the initial conditions and the course of random sampling. Multiple runs are commonly recommended in studies using evolutionary algorithms, as they make it possible to identify stable solutions and distinguish them from random ones. In the present study, it was assumed that 100 runs constituted a sufficient number to assess classification repeatability and to identify the stable core of the solution.

For each weight variant, the following were calculated: the frequency with which a port was assigned to a given class, the number of ports retaining the same class across all runs, the maximum change in the value of the synthetic indicator, and the consistency of core ports with the actual LNG layer (Table 5). The reference variant was defined as the weight configuration that combined the highest classification stability with the highest practical consistency.

Table 5. Results of weight calibration.

Weight Variant ($\delta_1, \delta_2, \delta_3$)	Number of Stable Core Ports	Consistency with the LNG Layer	Maximum Change W_p	Variant Assessment
0.45/0.35/0.20	5	5/5	0.07	adopted
0.40/0.40/0.20	5	5/5	0.08	high consistency
0.50/0.30/0.20	4	4/5	0.11	excessive dominance of the demand component
0.40/0.30/0.30	5	4/5	0.09	greater operational sensitivity

Accordingly, the following was adopted as the baseline variant on the basis of the calibration procedure:

$$\delta_1 = 0.45 \quad (10)$$

$$\delta_2 = 0.35$$

$$\delta_3 = 0.20$$

The 0.45/0.35/0.20 variant provided the best balance between classification stability and consistency with the actual port structure. For this reason, it was adopted as the baseline variant. This means that the greatest importance in the model was assigned to the demand component, the second greatest to the infrastructure component, and the third to the operational component. This result is consistent with the systemic interpretation: without sufficient demand, the development of a bunkering function is not justified; without infrastructure, it is not feasible; and without appropriate operational conditions, it cannot be maintained in a stable manner.

2.5. Model Validation and Robustness Assessment

Model validation was carried out to assess the model's computational stability, robustness to parameter changes, and consistency of the results with the actual structure of the Baltic Sea port system [54]. In models based on genetic algorithms, the validation procedure is of fundamental importance, because the final result is not the outcome of a single deterministic computation, but rather the result of multiple runs of a stochastic procedure [55–59].

Three levels of validation were applied in the study: internal validation, sensitivity validation, and external validation [60–64]. Internal validation was used to assess the stability of port classification across successive runs of the algorithm. Sensitivity validation was intended to determine whether the final classification depended excessively on the adopted weights.

External validation was used to verify whether ports classified as core ports corresponded to ports with a genuinely confirmed LNG layer and high traffic significance.

The frequency with which a port was assigned to a given class and the share of the dominant class were evaluated. A port was considered stable if its assignment to a given class was repeated in the vast majority of runs.

Sensitivity validation consisted of analyzing the results for the four weight variants described in the calibration procedure. Its purpose was to determine whether a moderate change in the relative importance of the demand, infrastructure, and operational components led to a substantial change in the configuration of core ports. External validation, in turn, consisted of comparing the model results with the actual characteristics of ports, particularly looking at traffic intensity and the publicly confirmed LNG layer.

In addition, seasonality validation was carried out. Its purpose was to determine whether monthly traffic variability affected the interpretation of a port's operational feasibility. For this purpose, a reference port was used for which consistent monthly data on vessel calls, passenger traffic, and cargo traffic were available (Table 6). This validation played a supporting role and was intended to assess whether the annual classification remained valid when seasonal changes in port workload were also taken into account.

Table 6. Scope of model validation.

Type of Validation	Scope of Assessment	Measure	Unit
Internal validation	repeatability of port classification	number of algorithm runs	n
Sensitivity validation	robustness of results to changes in weights	number of weight variants	n
External validation	consistency of results with the actual port structure and LNG layer	classification consistency	n/n
Seasonality validation	impact of monthly variability on the interpretation of operational feasibility	change in traffic load	%

Validation was not limited to a single consistency test. Each validation level refers to a different aspect of model quality. Internal validation examines computational stability; sensitivity validation tests robustness to parameter changes; external validation assesses practical validity; and seasonality validation verifies the correctness of adopting an annual perspective under conditions of monthly variability (Table 7). Such a framework strengthens the credibility of the model and reduces the risk of overinterpreting individual results.

Table 7. Distribution of results for 100 algorithm runs in the baseline variant.

Port	Core Class	Supporting Class	Local Class	Dominant Class	Share of the Dominant Class [%]
Helsinki	96	4	0	core	96
Gdańsk	94	6	0	core	94
Szczecin–Świnoujście	91	9	0	core	91
Tallinn	89	11	0	core	89
Klaipėda	87	13	0	core	87
Trelleborg	13	84	3	supporting	84
Rostock	18	79	3	supporting	79
Gdynia	12	82	6	supporting	82
Riga	0	12	88	local	88
HaminaKotka	0	10	90	local	90

The port classification exhibits a clear, stable core. The five highest-ranked ports retain the core class in the vast majority of runs, whereas Riga and HaminaKotka consistently

remain in the local class. Supporting ports show greater dispersion of results, which is an expected phenomenon, as they constitute an intermediate group between ports that are clearly core and those that are clearly local. From a methodological perspective, this means that the model distinguishes well between extreme cases, while the greatest uncertainty concerns intermediate ports, which is characteristic of multicriteria classification.

The validation conducted in this manner confirms that the final solution is not the result of a single algorithm run or a random weight configuration. Only such a classification variant was regarded as the final configuration that was simultaneously computationally stable, robust to moderate parameter changes, and consistent with the actual structure of Baltic Sea ports.

The validation covered both computational repeatability and the model's robustness to changes in the weight structure. The inclusion of several weight variants was necessary because port classification cannot be considered valid if it changes substantially under a minor modification of model parameters. For this reason, the validation procedure was not limited to testing a single baseline variant but also included an assessment of solution stability under changes in the relationship between the demand, infrastructure, and operational components.

Internal validation was carried out 100 times for the baseline variant. A total of 100 runs were performed, which ensured the stability of the results. Multiple independent runs are widely recommended in the methodological literature as a means of identifying stable solutions. In the present study, it was assumed that 100 runs constituted a sufficient number to determine the frequency with which ports appeared in particular classes and to distinguish stable solutions from random ones. Further increasing the number of runs no longer led to a substantial change in the structure of the results, while it did increase the computational cost.

In internal validation, three basic measures were evaluated: the frequency with which a port was assigned to a given class, the port's dominant class, and the dispersion of the synthetic indicator values. In sensitivity validation, the number of ports retaining the same class across all weight variants and the maximum change in the synthetic indicator value after changing the weight set were assessed. In external validation, the consistency of ports classified as core with ports possessing actual LNG infrastructure-related premises and high traffic intensity was examined (Table 8).

Table 8. Selected model validation values.

Validation Element	Measure	Value	Unit	Interpretation
Internal validation	number of algorithm runs	100	n	sufficient number for stability assessment
Sensitivity validation	number of analyzed weight variants	4	n	assessment of parametric robustness
Sensitivity validation	number of ports retaining the core class across all weight variants	5	n	high stability of the solution core
Sensitivity validation	maximum change in the value of W_p after changing weights	0.07	dimensionless	limited parametric sensitivity
External validation	consistency of core ports with the publicly confirmed LNG layer	5/5	n/n	full practical consistency
Seasonality validation	maximum increase in passenger traffic at the reference port relative to January	184	%	high seasonality of RO-PAX traffic
Seasonality validation	change in the class of the reference port after accounting for seasonality	0	n	no change in classification

The model preserves both computational and interpretative stability. The limited change in the value of the synthetic indicator after modification of the weights means that the result does not depend excessively on a single set of parameters. At the same time, the full consistency of core ports with the publicly confirmed LNG layer confirms the model's practical validity. These results indicate that port classification is not the outcome of a random algorithm configuration, but rather reflects a stable solution structure.

The results of the 100 algorithm runs for the baseline variant were then presented in the form of a class distribution for individual ports. This manner of presentation is more useful than showing 100 individual runs because it makes it possible to assess classification stability directly and to determine how often a given port was assigned to the core, supporting, or local class.

3. Results

3.1. Port Classification

The application of the model to Baltic Sea ports led to the identification of three functional classes: core ports, supporting ports, and local ports (Table 9). This classification is not a simple ranking of ports by size but results from the simultaneous consideration of traffic intensity, transport structure, LNG readiness, and operational conditions. The final class configuration constitutes the result of multiple runs of the algorithm and the aggregation of results for the baseline variant.

Table 9. Results of the functional classification of Baltic Sea ports.

Port	Demand Indicator (D_p)	Infrastructure Indicator (I_p)	Operational Indicator (O_p)	Synthetic Indicator (W_p)	Final Class
Helsinki	0.476	0.800	1.000	0.694	core
Gdańsk	0.613	0.800	0.700	0.676	core
Szczecin–Świnoujście	0.231	1.000	1.000	0.654	core
Tallinn	0.343	0.800	1.000	0.634	core
Klaipėda	0.301	1.000	0.800	0.625	core
Trelleborg	0.400	0.300	1.000	0.500	supporting
Rostock	0.276	0.300	0.900	0.469	supporting
Gdynia	0.407	0.400	0.600	0.460	supporting
Riga	0.134	0.300	0.400	0.241	local
HaminaKotka	0.162	0.300	0.400	0.233	local

Core ports are not identified solely by the highest value of a single variable. Their position results from a relatively favorable combination of all three components of the model. Helsinki achieved the highest synthetic score not because of container dominance, but because it combines high traffic regularity, a strong RO-RO/RO-PAX layer, and confirmed LNG readiness. Gdańsk attained a very high position due to its strong demand component and developed LNG layer. Szczecin–Świnoujście and Tallinn obtained high scores primarily because of their operational feasibility and importance in regular ferry and RO-RO systems. Klaipėda, in turn, combines a strong cargo component with actual LNG infrastructure.

This distribution of results indicates that the LNG distribution system in the Baltic Sea should not be interpreted as an arrangement dependent on a single dominant port. On the contrary, the results point to a polycentric node system in which different ports perform core functions for different reasons: container-related, ferry-related, RO-RO-related, or infrastructure-related. From a practical perspective, this means that the development of the LNG network should be selective and hierarchical rather than uniform.

3.2. Significance of the Demand Component

The demand component of the model is used to determine whether a port generates demand sufficient to justify the development of an LNG bunkering function. In the model, demand was not equated solely with the number of vessel calls or solely with cargo throughput volume. Instead, a combination of the number of vessel calls, container traffic, and RO-RO/ferry traffic was applied, because only such a configuration makes it possible to distinguish a port with a high one-off volume from a port with a high degree of traffic regularity (Table 10).

Table 10. Results of the demand component of the model.

Port	Number of Vessel Calls/Traffic Intensity	Dominant Traffic Profile	Assessment of the Demand Component
Gdańsk	high	container, deep-sea	very high
Gdynia	high	container, RO-RO, short-sea	high
Szczecin–Świnoujście	very high in the ferry and RO-RO system	ferry, RO-RO, bulk	moderate to high
Klaipėda	high	container, RO-RO	high
Riga	moderate	container, bulk	low to moderate
Tallinn	very high	RO-RO, RO-PAX, ferry	high
Helsinki	very high	RO-RO, RO-PAX, ferry, container	high
HaminaKotka	moderate	container, industrial	low to moderate
Rostock	very high	RO-RO, ferry	moderate
Trelleborg	very high	RO-RO, ferry	high

A high value of the demand component may result from different configurations of port traffic. Gdańsk achieves a very high assessment due to its dominant role in container shipping. Helsinki and Tallinn build their position primarily on the very high regularity of ferry and RO-PAX traffic. Trelleborg and Rostock attain high values due to intensive RO-RO traffic, but their final position in the model already depends on the remaining two components, especially the LNG layer.

This result shows that demand alone cannot be regarded as a sufficient criterion. A port may have very strong RO-RO or container traffic, but if it is not infrastructurally prepared or if its spatial role in the network is secondary, it will not be classified as a core port. On the other hand, without a strong demand component, there is no justification for developing an LNG bunkering function, even when the port possesses certain infrastructure elements.

3.3. Assessment of Port Infrastructure Readiness

The infrastructure component of the model was based on measurable premises indicating a port's actual preparedness for LNG handling. High values were assigned to ports possessing a bunkering service, an LNG terminal, formal operational procedures, or confirmed bunkering operations (Table 11). In this way, the infrastructure component is not declarative in nature, but refers to the port's actual capabilities.

The differences between ports result not only from traffic, but also from the level of preparedness for LNG handling. It is precisely this component of the model that distinguishes Gdańsk from Gdynia, and Klaipėda from Riga. In practical terms, this means that the development of the LNG system cannot be assessed solely through the prism of port traffic. Even a very strong traffic port does not become a fuel port without an appropriate organizational and technical layer.

Table 11. LNG infrastructure readiness scores for the analyzed ports.

Port	Main Infrastructure Premise	Assessment (I_p)
Gdańsk	LNG bunkering service	0.8
Gdynia	limited, indirect readiness	0.4
Szczecin–Świnoujście	direct connection to LNG infrastructure	1.0
Klaipėda	confirmed LNG STS bunkering	1.0
Riga	no strongly confirmed LNG layer	0.3
Tallinn	formal authorization for LNG TTS/STS	0.8
Helsinki	LNG manual and procedures	0.8
HaminaKotka	limited public LNG layer	0.3
Rostock	no LNG layer as strongly confirmed as in the leading ports	0.3
Trelleborg	regulatory solutions and adaptation to LNG	0.3

The results of this component of the model indicate that core ports in the Baltic Sea are not merely “large ports” but ports in which LNG is already genuinely embedded in port practice. This is an important conclusion, because it suggests that investments in LNG yield the highest utility where at least a partially developed infrastructure layer already exists.

3.4. Significance of Operational Conditions

The operational component of the model describes whether a port is capable of maintaining bunkering as a regular and organizationally justified service (Table 12). It takes into account traffic regularity, the port’s position within the regional system, spatial accessibility, and the operational conditions associated with vessel handling.

Table 12. Results of the operational component.

Port	Traffic Regularity	Position in the Regional System	Assessment (O_p)
Helsinki	very high	main hub of the Gulf of Finland	1.0
Gdańsk	high	southern container hub	0.7
Szczecin–Świnoujście	very high	western gateway of the system	1.0
Tallinn	very high	north-eastern RO-PAX hub	1.0
Klaipėda	high	eastern system port	0.8
Trelleborg	very high	western RO-RO port	1.0
Rostock	high	western RO-RO/ferry port	0.9
Gdynia	moderate	supporting port of the southern system	0.6
Riga	moderate	port with a weaker network function	0.4
HaminaKotka	moderate	north-eastern regional port	0.4

High operational feasibility is not equivalent to a high final position in the model. Trelleborg and Rostock achieve high operational values due to the regularity of RO-RO and ferry traffic, but they do not advance to the core class because of a weaker LNG infrastructure layer. This means that the operational component performs a corrective and confirmatory function. It does not replace demand or infrastructure, but strengthens the result where a port has a real capacity to maintain bunkering in a repeatable manner.

From the perspective of organizing the LNG distribution system, this means that ports with high operational feasibility may perform a very important role even when they are not the main container ports. This component of the model is particularly important for ferry and RO-RO ports, which in the Baltic Sea create stable traffic patterns conducive to bunkering.

3.5. Validation Results and Their Significance

Model validation demonstrated a high degree of stability in port classification. Core ports were consistently assigned to the same class in the vast majority of algorithm runs. Supporting ports exhibited slightly greater variability, which is an expected phenomenon, as they constitute an intermediate group between ports that are clearly core and those that are clearly local (Table 13).

Table 13. Results of port-classification validation.

Port	Share of the Dominant Class	Dominant Class
Helsinki	96%	core
Gdańsk	94%	core
Szczecin–Świnoujście	91%	core
Tallinn	89%	core
Klaipėda	87%	core
Trelleborg	84%	supporting
Gdynia	82%	supporting
Rostock	79%	supporting
HaminaKotka	90%	local
Riga	88%	local

The model distinguishes very well between extreme cases, that is, ports that are unequivocally core and those that are unequivocally local. The greatest uncertainty concerns supporting ports. Ports in this class are located in a transitional zone: they possess significant traffic-related or operational characteristics but have not yet achieved full infrastructural or network-related superiority.

This means that the model may be used not only to describe the current state of the system but also to identify ports with promotion potential. In practical terms, supporting ports are the most interesting from the perspective of investment policy, because they are the ports most likely to improve their position if the LNG layer is strengthened.

The seasonality analysis was carried out for the reference port and was intended to determine whether monthly variability affects the interpretation of the operational feasibility of the LNG system (Table 14). The results showed that seasonality in the Baltic Sea primarily concerns the intensity of use of ferry and RO-PAX services rather than the number of vessel calls itself.

Table 14. Significance of seasonality for model interpretation.

Element of Analysis	Result	Significance for the Model
Maximum increase in passenger traffic relative to January	+184%	high seasonality of the RO-PAX segment
Change in the number of vessel calls	limited	stability of the port's position within the network
Impact on port class	no change	seasonality affects operational feasibility, not classification

Seasonality does not alter a port's basic position in the model, but it does affect the interpretation of its operational load. This is an important finding because it means that annual classification may be regarded as stable, whereas the operational planning of bunkering should take into account monthly traffic peaks.

This indicates that the annual model is well-suited to identifying systemic nodes, but its practical application should be supplemented by seasonal analysis in ports where RO-PAX and ferry transport predominates.

Overall, the results indicate that the regional LNG distribution system in the Baltic Sea should have a hierarchical and polycentric structure. Core ports form the actual backbone of the network. Supporting ports constitute a second ring that may assume part of the system's functions, whereas local ports remain significant only at the subregional scale.

The results show that LNG development should not be pursued uniformly across all ports. The greatest utility is achieved by investments concentrated in ports that combine three features simultaneously: strong demand, a developed LNG layer, and favorable operational conditions. The applied model therefore makes it possible not only to describe the structure of ports but also to indicate where the development of the LNG bunkering function is most justified from the perspective of the regional system.

4. Discussion

The obtained results indicate that the organization of LNG distribution in the Baltic Sea should be interpreted as a network problem rather than as the sum of independent infrastructure decisions made by individual ports. The applied model demonstrated that a port's position within the system is not determined by a single attribute, but by the coexistence of three groups of conditions: sufficiently strong demand, actual infrastructure readiness, and favorable operational conditions. This means that even a port of very high cargo-handling significance does not automatically perform a core function in the LNG system if it lacks a sufficient infrastructure layer or if its role within the spatial system remains secondary.

The model results clearly indicate a polycentric LNG distribution structure. This is one of the most important findings of the study. The ports classified as core do not form a single spatial cluster or a functional group. Helsinki and Tallinn build their position primarily on the high regularity of RO-PAX and ferry traffic, Gdańsk on its dominant role in container transport and its LNG layer, Szczecin–Świnoujście on its function as the western gateway of the system and its direct connection to LNG infrastructure, and Klaipėda on the combination of cargo significance and actually confirmed bunkering capability. This means that the LNG distribution system in the Baltic Sea should not be designed as a structure subordinated to a single dominant port, but rather as a network of several complementary nodes. In practical terms, the proposed classification may be used as a screening layer within the existing LNG supply chain. Core ports indicate locations where bunkering services can be most directly linked with existing or planned LNG terminals, storage facilities, truck-to-ship operations, or ship-to-ship bunkering services. Supporting ports may act as secondary nodes connected to the nearest core port, whereas local ports should not be prioritized for full-scale LNG infrastructure unless demand or readiness conditions change.

This result has important methodological and practical implications. From a methodological perspective, it confirms that the adopted model structure was justified. If the classification had been based solely on container throughput, the highest positions would have been occupied primarily by deep-sea and liner ports. If the classification had been based exclusively on RO-RO and ferry traffic, the model would have favored ferry ports while overlooking the importance of major cargo ports. Only the combination of data on vessel calls, traffic structure, LNG readiness, and operational conditions made it possible to capture the actual function of a port in the regional fuel distribution network. This means that the model does not favor one type of port but differentiates ports according to their ability to perform a specific systemic function.

The results also indicate that LNG has selective rather than universal justification. The data show that the development of an LNG bunkering function is most justified in ports that simultaneously generate stable traffic, possess a confirmed LNG layer, and are located

within a spatial arrangement that enables effective interaction with the regional hinterland. In this sense, LNG proves to be a conditionally viable fuel. It cannot be assumed that its development should proceed uniformly across all ports in the region. On the contrary, the results indicate that the greatest systemic utility is achieved by investments concentrated in core ports, whereas in supporting ports, it may be more rational to develop phased solutions or solutions linked to the nearest core node.

This conclusion is supported primarily by the differences in results between supporting and core ports. Trelleborg and Rostock achieve very high operational parameters due to regular RO-RO and ferry traffic, but they did not attain core status because of a weaker LNG layer. Gdynia is characterized by a strong position in container and RO-RO traffic, yet its final score remains lower than that of Gdańsk due to its smaller infrastructure advantage and weaker network function. This means that supporting ports are not weak ports, but rather ports whose role in the system depends on strengthening one of the model components. From a practical point of view, these are the ports with the greatest potential for functional transformation.

An important finding of the study is also that seasonality does not change the class of a port, but it does change the interpretation of its operational load. The analysis of the reference port showed that monthly traffic variability, particularly in the RO-PAX segment, leads to clear fluctuations in service intensity. However, it does not affect the basic position of the port within the network structure. This means that the annual model is appropriate for the functional classification of ports, whereas the operational planning of bunkering should take seasonal variability into account where ferry and passenger transport predominates. In practical terms, this supports the separation of two management levels: the strategic level, at which core and supporting ports are identified, and the operational level, at which bunkering schedules are adjusted to monthly and seasonal changes in traffic intensity.

The validation carried out strengthens the credibility of the obtained results. The stability of classification across multiple runs of the algorithm means that the identified core of the system is not the result of a single random configuration. Robustness to changes in weights, in turn, indicates that the solution does not depend excessively on an arbitrarily assumed relationship between the demand, infrastructure, and operational components. Consistency of the results with the actual LNG layer in Baltic ports confirms the model's practical validity. As a result, it can be concluded that the classification of ports into core, supporting, and local categories is not merely a formal construct but reflects the actual structure of the regional port system.

At the same time, the model has certain limitations. First, it is based on data aggregated at the port level rather than on a full record of individual vessel trajectories and actual bunkering operations. Second, the model does not incorporate actual port-to-port sailing distances or operational maritime routes between the selected ports. Therefore, the spatial-accessibility component should be interpreted as a strategic approximation of inter-port relationships rather than as a complete maritime-routing or connectivity model. In future applications, this component should be reformulated using actual sailing-distance matrices, AIS-based vessel trajectories, or established maritime corridors. Such an extension would make it possible to assess not only whether the selected ports are geographically distributed, but also whether they are functionally connected within existing maritime transport networks. Third, seasonality was introduced as an interpretative variable rather than as a direct component of the classification function. Fourth, the model does not include fuel-price dynamics, total bunkering costs, lifecycle emissions, or emission-related regulatory costs. This is an important limitation because maritime fuel adoption and bunkering–infrastructure deployment are highly sensitive to

operational costs and environmental regulations. Therefore, the synthetic indicator W_p should be interpreted as a strategic indicator of location and network potential rather than as a complete techno-economic feasibility measure. Consequently, the model should be treated as a preliminary screening tool rather than as a ready-to-use decision-making tool for investment planning or operational LNG bunkering management. Its results indicate where further techno-economic, environmental, and route-based analyses are most justified, but they do not confirm simplified costs, emissions, methane impacts, or real shipping-route feasibility. Future research should extend the model by adding fuel-cost scenarios, lifecycle-emission accounting, methane-emission assessment, carbon-pricing mechanisms, operational expenditure parameters, and real shipping-route analyses. These limitations do not, however, undermine the cognitive value of the model but rather define directions for its further development. In particular, future research may extend the model by adding a detailed cost module, a full emissions analysis, and a direct comparison of LNG with methanol, ammonia, and other alternative fuels while maintaining the same decision structure.

Against the background of previous analyses, the results of the study contribute two important elements. First, they confirm that the role of a port in the fuel system should be analyzed through the prism of multiple interdependent characteristics rather than a single dominant indicator. Second, they show that a model developed for LNG may serve as a universal analytical tool which, after modification of input parameters, can also be applied to other alternative fuels. This second aspect is of particular practical importance because it makes it possible to use one model structure to compare different variants of fuel transition in seaports.

5. Conclusions

The study demonstrated that the organization of LNG distribution in the Baltic Sea region should be analyzed as a port–transport system rather than as a set of independent infrastructure decisions made by individual ports. This follows from the fact that a port’s significance within the bunkering network is a function of demand potential, infrastructure readiness, and the operational conditions for bunkering.

The applied model made it possible to distinguish three functional classes of ports: core, supporting, and local. The results indicated that the core of the regional LNG distribution system is formed by Helsinki, Gdańsk, Szczecin–Świnoujście, Tallinn, and Klaipėda. These ports are not functionally homogeneous, but they are linked by a favorable combination of demand, infrastructure, and operational feasibility. Trelleborg, Rostock, and Gdynia were classified as supporting ports, which means that they possess significant systemic potential but do not yet achieve superiority across all components of the model. Riga and HaminaKotka remained in the local class, indicating their limited significance within the regional LNG distribution system.

The results of the study show that the LNG distribution system in the Baltic Sea is polycentric in character. This means that the most justified configuration is not based on a single dominant port but on several complementary nodes located in different parts of the sea basin. Such a structure is better aligned with the spatial pattern of transport flows, reduces the risk of excessive concentration of fuel supply functions, and increases the resilience of the system to operational disruptions.

From a systemic perspective, LNG remains a transitional fuel with a high level of implementation maturity, which justifies the analysis of infrastructure and bunkering organization regardless of the long-term decarbonization scenario. The development of LNG infrastructure is most rational in ports with high traffic intensity and regularity and with a genuinely confirmed LNG layer. The results do not support the rationale for

uniformly developing full LNG infrastructure in all ports of the region. Therefore, the classification should be interpreted as an initial screening result indicating ports for further detailed assessment, not as a final investment or operational recommendation. From a practical perspective, this implies the need to prioritize investments and to concentrate efforts in ports of the highest systemic importance.

The validation carried out confirmed the stability of the model. The repeatability of results across successive algorithm runs, the robustness of classification to moderate changes in weights, and the consistency of the results with the actual structure of ports indicate that the model maintains both computational consistency and practical validity. This means that it may be applied as a tool supporting the assessment of port configurations within the regional LNG bunkering system.

An important feature of the developed model is its universality. The scientific contribution of the study lies in linking port traffic structure, infrastructure readiness, and operational feasibility within one classification framework for alternative-fuel network planning. The practical contribution is the identification of ports where LNG bunkering development should be prioritized, delayed, or treated as supporting rather than core infrastructure. The model structure is not linked exclusively to LNG but to the organization of an alternative fuel within the port–transport system. After adjustment of technological, cost-related, emission-related, and operational parameters, it may also be applied to methanol, ammonia, bio-LNG, or synthetic fuels. For this reason, the model may provide a basis for further comparative research on the structure of regional alternative fuel networks in maritime shipping. In this way, the model supports more selective and sustainability-oriented infrastructure planning by indicating where alternative-fuel investments may generate the highest systemic value.

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