

Bottom-up estimation of CO₂ emissions from container ships: a proof of concept using real operational data on the Brazil–Asia route

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Bottom-up estimation of CO₂ emissions from container ships: a proof of concept using real operational data on the Brazil–Asia route

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Abstract

Granular quantification of greenhouse gas (GHG) emissions from maritime transport matters both for the assessment of decarbonisation strategies and for the attribution of the carbon footprint to logistics flows. This study proposes a bottom-up approach that integrates operational reconstruction of the voyage, physical-energy modelling, Tank-to-Wake (TTW) and Well-to-Wake (WTW) assessment, and allocation of emissions to the flows carried. The approach was applied to the M/V EVER FAME along a sequential rotation between the east coast of South America and Asia, comprising 11 port calls, 10 legs and 13,913.3 nautical miles. Under the assumptions adopted, the model estimated a fuel consumption of 3,407.9 t and emissions of 10,612 tCO₂ TTW and 12,741 tCO₂eq WTW, corresponding to intensities of 768 kgCO₂/TEU, counting laden and empty containers together, and 37.0 gCO₂/TEU·km. Among the decarbonisation scenarios, the largest WTW reductions were obtained with e-ammonia (91.9%) and e-methanol (72.0%), whereas LNG performance varied with engine technology and methane slip. The approach further allocated emissions in full across 3,251 shipment records, preserving the voyage balance with a conservation deviation of 0.0000%. The results demonstrate the feasibility of integrating vessel operating conditions, energy consumption, life-cycle emissions and logistics flows within a traceable structure, thereby supporting the assessment of decarbonisation alternatives and the measurement of the carbon footprint of maritime transport.

Keywords: maritime transport; greenhouse gas emissions; bottom-up modelling; Tank-to-Wake; Well-to-Wake; decarbonisation; emissions allocation

1 Introduction

Maritime transport plays a central role in international trade, accounting for roughly 80% of the volume carried worldwide while being responsible for approximately 3% of global CO₂ emissions. The expansion of intercontinental logistics chains, the growing demand for freight transport and the sector's heavy reliance on fossil fuels keep its decarbonisation a major challenge for the coming decades (International Maritime Organization, 2023; Dettner and Hilpert, 2023; Faber et al., 2021; Bayraktar et al., 2026). Changes in routes and sailing profiles arising from logistics and geopolitical disruptions may also significantly alter the distances sailed and, consequently,

the emissions associated with maritime transport (European Commission, 2025; International Maritime Organization, 2023).

In response to this scenario, the International Maritime Organization (IMO) established, in its revised 2023 strategy, targets for reducing carbon intensity and for advancing towards climate neutrality in maritime transport. In parallel, regulatory mechanisms have been broadening the assessment of emissions from those directly associated with fuel use on board (Tank-to-Wake, TTW) to a life-cycle perspective (Well-to-Wake, WTW), incorporating impacts related to fuel production, processing and distribution. This transition is reflected

both in IMO regulatory initiatives and in FuelEU Maritime, increasing the need for methods capable of assessing different energy alternatives under comparable emission boundaries (International Maritime Organization, 2023, 2024; European Parliament and Council of the European Union, 2023). A scope delimitation relevant to the case analysed should be noted: the European instruments — the maritime EU ETS and FuelEU Maritime — apply to voyages departing from or arriving at ports in the European Union and therefore do not bear directly on the Brazil–Asia route examined here. Their mention serves as a regulatory reference and as an indication of the sector’s direction, not as a compliance requirement for the modelled voyage; recent work discusses precisely the coordination and double-pricing problems arising from the coexistence of the European regime and the NZF (Guo and Wang, 2026). In the Brazilian context, the corresponding instrument is the Brazilian Emissions Trading System (SBCE), established by Law No. 15,042/2024 (Brasil, 2024), whose implementation is proceeding alongside the national port and maritime decarbonisation agenda (Pacto Global da ONU – Rede Brasil, 2024). This paradigm shift and the need to incorporate upstream variables are already central elements of the framing presented in the underlying full-length study. Within this framework, the IMO Net-Zero Framework (NZF), approved at the 83rd session of the Marine Environment Protection Committee (MEPC 83) in April 2025, couples a global standard for the life-cycle GHG intensity of fuels — the Greenhouse Gas Fuel Intensity (GFI), in gCO₂eq/MJ — to a carbon pricing mechanism, in the form of an amendment to MARPOL Annex VI (International Maritime Organization, 2024; Bayraktar et al., 2026). Its adoption was deferred by one year at the extraordinary session MEPC/ES.2, in October 2025, with discussions resuming at MEPC 84 in 2026 (Psaraftis, 2026; Climate Action Tracker, 2026). The deferral does not change the regulatory direction of the sector, but it widens the uncertainty surrounding the compliance timetable and reinforces the relevance of instruments able to produce, already today, intensity indicators compatible with the design of the Framework.

In this context, the quality of measurement becomes particularly relevant. Aggregated or top-down models are limited in their ability to represent differences arising from the specific operating conditions of individual vessels. Bottom-up approaches, by contrast, allow variables such as speed, power, operating time, vessel technical characteristics, environmental conditions and cargo composition to be incorporated, offering greater granularity in the estimation of energy consumption and emissions. Recent studies point to the importance of such approaches for analysis of energy scenarios, operational optimization, and allocation of emissions along the logistics chain (Dettner and Hilpert, 2023). The growing

availability of operational data, sensors and information from the Automatic Identification System (AIS) further expands the possibilities for representing and analysing vessel operating conditions.

Despite these advances, the robustness of bottom-up approaches remains directly tied to the quality, granularity and completeness of the data used to reconstruct vessel operation. Variations in the representation of parameters such as speed, draught, operating time and cargo composition can have significant effects on consumption and emission estimates. Moreover, many models remain largely theoretical or depend on operational data that are difficult to obtain, limiting their application in real settings. A further question arises when moving from the aggregated estimation of vessel emissions to their attribution to logistics flows: knowing the total emission of a voyage does not, in itself, determine how that emission should be distributed among cargoes, bills of lading and the remaining flows that used the transport service.

Addressing this gap, the present study proposes and assesses a bottom-up approach based on the integration of commercial, port and technical data in order to reconstruct a sequential maritime voyage, estimate its energy consumption and emissions, and associate them with the logistics flows carried. The approach is applied to the M/V EVER FAME along a rotation between the east coast of South America and Asia, integrating leg-level operating conditions, vessel characteristics and cargo composition. The structure further allows fuels and propulsion technologies to be compared under TTW and WTW perspectives, and the plausibility of the operational assumptions to be assessed against external references, including AIS data. These elements constitute the central objectives of the proposed approach.

The main contribution of this work lies in integrating these dimensions within a single, traceable methodological structure. Specifically, the study: (i) reconstructs a sequential physical rotation from logistics and port data; (ii) estimates energy consumption and emissions taking into account operating conditions that vary along the voyage; (iii) compares fuel and operating alternatives under TTW and WTW perspectives; and (iv) establishes a procedure for allocating emissions at bill-of-lading and entity level, including empty container flows. An analytical chain is thereby established between vessel operation, energy demand, emissions and logistics flows, broadening the applicability of bottom-up modelling to decarbonisation analysis and to the measurement of the carbon footprint of maritime transport.

2 Related work and research gap

The estimation of emissions from maritime transport can be structured at different levels of granularity. Top-down approaches use aggregated fuel consumption data to estimate emissions from fleets or routes, offering lower com-

plexity but limited capacity to represent the specific operating conditions of each vessel. By contrast, bottom-up approaches estimate energy consumption and emissions from parameters associated with the vessel and the voyage, such as installed power, engine load factor, specific fuel oil consumption (SFOC), speed, distance and operating time (Faber et al., 2021). This finer resolution makes it possible to represent operational differences that tend to be concealed in aggregated inventories.

The use of Automatic Identification System (AIS) data expanded this capacity by allowing vessel position, speed and operating status to be reconstructed at higher temporal resolution. AIS-based bottom-up models constitute a relevant approach for high-granularity maritime inventories, although their application depends on the coverage, frequency and quality of the available records. Inconsistencies, missing observations and inadequate temporal resolution may introduce significant uncertainties, making data quality control procedures necessary (emLab and Global Fishing Watch, 2026; Chen and Yang, 2024). The availability of high-resolution AIS therefore does not remove the dependence on input data quality and may limit application in certain operational contexts.

Among the variables that condition bottom-up models, speed exerts a particularly relevant influence on propulsion demand. The literature widely adopts an approximately cubic relationship between speed and power, such that relatively small changes in speed may produce non-linear variations in required power and, consequently, in fuel consumption and emissions (Bialystock and Konovessis, 2016). This relationship should nevertheless be read as an approximation, since its behaviour depends on the hydrodynamic characteristics of the vessel, the loading condition and the operating regime. Psaraftis and Lagouvardou (2023) show that the exponent of the speed–power relationship is not a universal constant, reinforcing the need to account for specific operating conditions when applying such models.

This sensitivity also underpins slow steaming as an operational strategy. Reducing speed can substantially lower propulsion demand, fuel consumption and emissions, although it affects voyage time and economic performance. Recent studies reinforce the relevance of slow steaming as a short-term option for reducing maritime emissions and indicate that the direct use of nominal or design speed may not adequately represent the operational behaviour of vessels (Elkafas et al., 2023; Pelić et al., 2023; Degiuli et al., 2024).

Voyage-level assessments confirm this sensitivity and make its limits explicit: Coşofreţ et al. (2026) compare, for a 5,000 TEU post-Panamax container ship, three operating speeds combined with three fuel configurations,

reporting the joint effect on consumption, CO₂, EEOI and Tank-to-Wake intensity, and showing that speed reduction operates as a trade-off solution rather than as a dominant measure.

Speed, however, is not the only source of variability. Energy performance is also conditioned by the loading condition, draught, trim, hull condition and environmental factors. Cepowski and Drozd (2023) identify hull fouling as one of the factors with the greatest influence on consumption in container ships, followed by draught and trim, while wind, waves and water temperature introduce additional effects. The increase in resistance arising from fouling may produce significant increments in consumption over the interval between dry-dockings (Cepowski and Drozd, 2023; International Towing Tank Conference, 2021), whereas weather routing strategies demonstrate potential for reducing consumption by taking meteorological conditions into account when defining the route (Pennino and Scamardella, 2022). ISO 15016 further provides procedures for assessing vessel performance under different operating conditions (Kim and Roh, 2020).

Evidence based on real operational data reinforces this order of magnitude from the intervention side: Zaragoza et al. (2026), analysing two LNG carriers before and after maintenance operations, report that complete hull and propeller cleaning reduces fuel consumption by more than 30% and CO₂ emissions by more than 15%, with propulsive efficiency gains between 18% and 34%, whereas partial interventions produce a limited effect confined to specific speed ranges.

The loading condition likewise influences resistance and energy performance. Borén et al. (2023) demonstrate the relevance of representing off-design operation, including situations in which the vessel operates at speeds differing from design conditions and under partial draught. For container ships, cargo composition adds a further dimension to the problem, particularly because of refrigerated containers (reefers), whose electrical demand contributes to auxiliary system consumption. Taken together, this evidence indicates that representing actual operating conditions is a relevant component of the consistency of bottom-up models.

Beyond operating conditions, the energy transition of the maritime sector requires the assessment to be extended to the life cycle of fuels. The Tank-to-Wake (TTW) perspective considers emissions arising from fuel use on board, whereas the Well-to-Wake (WTW) perspective also incorporates emissions associated with fuel production, processing and transport (International Maritime Organization, 2024). This distinction is particularly important for alternative fuels, since a reduction in emissions during vessel operation does not necessarily imply an equivalent reduction once the entire energy cycle is considered.

Liquefied natural gas (LNG), for instance, can reduce direct CO₂ emissions relative to conventional marine fuels, but its climate performance depends significantly on methane slip, the release of unburned methane during combustion (Pavlenko et al., 2020). The magnitude of this effect varies with engine technology: high-pressure systems such as the MAN ME-GI exhibit lower methane slip than low-pressure architectures such as X-DF and four-stroke LPDF engines. Consequently, propulsion technology may substantially alter the GHG balance associated with LNG use (Pavlenko et al., 2020; Ushakov et al., 2019). Lower-carbon alternatives such as e-methanol and e-ammonia offer greater potential for reducing life-cycle emissions, although they remain associated with significant technological and economic challenges (Lee et al., 2024; Zincir and Arslanoglu, 2024; Kanchiralla et al., 2024). The consolidation of this evidence, however, is still uneven: Sivappirakasam et al. (2026) map and classify marine fuels according to the pathways defined by the IMO, harmonise life-cycle emission and cost data and confront them with the regulatory limits of the IMO and FuelEU, concluding that the absence of harmonised life-cycle data remains an obstacle to comparison between alternatives. From a systemic standpoint, Kanchiralla et al. (2026) show, using a global energy systems model coupled to life-cycle assessment, that the fuel pathway of maritime transport depends on competition for clean energy with other sectors, so that the environmental performance of a synthetic fuel is not a fixed property of the energy carrier but a function of the production context in which it is obtained. It should further be noted that life-cycle GHG intensity is not merely a modelling parameter: it is the regulatory metric around which the NZF organises compliance, structured in two compliance tiers and associated with a mechanism of remedial and surplus units (Bayraktar et al., 2026).

Between the micro scale (position by position) and the macro scale (fleet or region), the literature recognises a third, meso-level resolution in which the unit of calculation is the voyage or the leg between port calls. Zhou et al. (2022) explicitly formulate a voyage-based meso-level CO₂ emission model with the aim of reducing dataset quality requirements and computational volume relative to micro-level models, while preserving the relevant sailing characteristics. Recent reviews reinforce that the maturity of the field depends less on the sophistication of the estimator and more on the articulation between data governance, the availability of emission datasets and modelling (Wang et al., 2026c), while AIS-based inventories exhibit controlled uncertainty when accompanied by formal validation procedures (Chen et al., 2026). It is within this intermediate band that the approach proposed here is situated: the unit of calculation is the leg of the rotation, and neither the instantaneous

position nor the aggregated fleet.

Applying these approaches in port waters presents additional difficulties, associated with the heterogeneity of operating modes and with the influence of local factors on the effect of emissions; Yuan et al. (2026) develop, on the basis of AIS and meteorological data, a hierarchical fuzzy logic model for environmental impact assessment in port waters, showing that manoeuvring, berthing and port entry and exit concentrate the greatest impacts.

A complementary line of research addresses the problem opposite to that of high resolution: the scarcity of static vessel parameters. Wang et al. (2026a) propose a multi-source data fusion framework with machine learning precisely to fill parameter gaps in bottom-up models, while Xu and Liu (2026) systematise the advance of predictive methods, including large language models, applied to the forecast of maritime emissions; voyage-level causal approaches have likewise been used to estimate carbon intensity from real operational panels (Yildiz et al., 2026). The methodological choice adopted in this work for a physical-energy engine — and not for a learned estimator — follows from three characteristics of the problem: the need for traceability between parameter and result, the requirement that the estimate be auditable by third parties, and the absence of a labelled historical consumption series for the vessel analysed. These conditions favour models whose causal chain is inspectable, albeit at the cost of lower capacity for empirical fitting.

Despite advances on these different fronts, a fragmentation between the dimensions addressed by the models can be observed. The literature provides consolidated foundations for bottom-up estimation, reconstruction of vessel activity, the speed-power relationship, the incorporation of operating conditions and TTW/WTW assessment. It remains relevant, however, to integrate these dimensions with the logistics structure of the voyage, allowing a move from the aggregated estimation of vessel emissions to their attribution to the flows actually carried. In particular, the association between leg-level operating conditions, energy consumption, life-cycle emissions and individual shipment records constitutes the methodological space explored in this study.

Accordingly, the proposed approach seeks to integrate within a single analytical chain (i) operational reconstruction of the voyage from logistics and port data, (ii) bottom-up physical-energy modelling, (iii) TTW/WTW scenario assessment and (iv) conservative allocation of emissions to bills of lading and other logistics flows, including empty containers. The aim is not to replace high-resolution AIS-based models, but to explore a complementary architecture capable of using available operational and logistics data to establish traceability between vessel operation and the attribution of emissions along the transport chain.

3 Materials and methods

3.1 Case study

The study was developed from a voyage of the container ship M/V EVER FAME, operated by Evergreen Marine, with a nominal capacity of 11,888 TEU and equipped with a MAN B&W 9S90ME-C10 main engine. The modelling assumed a maximum continuous rating (MCR) of 41,080 kW, a design speed of 23 kn, a maximum reference draught of 14.5 m and a nominal capacity of 1,400 reefer plugs.

The voyage analysed took place between September and November 2025 and was reconstructed as a sequential physical rotation comprising 11 port calls and 10 consecutive legs: BRRIO → BRNVT → UYMVD → ARBUE → BRPNG → BRSSZ → SGSIN → HKHKG → CNYTN → CNSHA → CNNGB, totalling approximately 13,913.3 nautical miles. This representation establishes a single spatio-temporal sequence in which each leg is processed only once for the calculation of consumption, emissions and subsequent allocation.

The modelling integrates operational and logistics data from Datamar, complementary information from the Brazilian National Waterway Transport Agency (ANTAQ), publicly available technical parameters of the vessel and factors drawn from the specialised literature. The consolidated Datamar database comprises 6,550 records corresponding to 3,229 bills of lading (B/Ls), containing origin and destination information, TEU, weight, container type, reefer identification, shippers and consignees, as well as the operational timestamps of arrival, berthing and departure (ATA, ATB and ATS) and the arrival and departure draughts. ANTAQ data complement the logistics representation with 22 aggregated repositioning records, corresponding to 3,057 empty TEU and approximately 5,983 t of tare weight.

The logistics database contains 10,761 laden TEU, equivalent to approximately 109,289 t of cargo, in addition to the 3,057 empty TEU. Refrigerated containers account for approximately 1,482 TEU, corresponding to about 14% of laden TEU and 22% of B/Ls. For each shipment record, the ports of loading and discharge were identified, with the record kept active along the legs comprised between these events. This procedure generates an analytical cargo profile (LoadProfile) containing TEU, weight and refrigerated TEU per leg. Cargo volumes are obtained by summing the TEU values associated with the active records; multiple records associated with the same B/L are therefore not interpreted as additional physical containers. The same aggregation logic is applied to refrigerated cargo. Since records may remain active across multiple segments, this profile represents analytical logistics flows and should not be read as a manifest of simultaneous physical occupancy of the ves-

sel.

3.2 Bottom-up emission framework

The approach was implemented in a modular computational architecture, structured as a traceable chain running from input data → voyage reconstruction → operational characterisation → physical-energy estimation → scenario simulation → emissions allocation. Five analytical services make up this structure: computation of maritime distances; temporal reconstruction and operational characterisation; bottom-up estimation of consumption and emissions; TTW/WTW scenario simulation; and allocation of emissions to logistics flows. Figure 1 presents the integrated view of this architecture, highlighting the flow between data sources, database preparation, analytical services and the outputs produced by the model.

Distances between consecutive ports were determined using the *searoute* library, which follows navigable maritime routes rather than straight-line geodesic distances. For each leg i , the temporal reconstruction considers the interval between departure from the port of origin and arrival at the subsequent port, while the port stay corresponds to the interval between arrival and departure. The implied speed is given by:

$$V_i = \frac{D_i}{T_{nav,i}}$$

where D_i is the maritime distance of the leg and $T_{nav,i}$ its reconstructed sailing time. These speeds do not represent direct measurements of Speed Over Ground (SOG), since the intervals may incorporate waiting, anchorage and differences in the temporal granularity of the records.

Propulsion demand is estimated from the speed-power relationship discussed in Section 2. To limit the propagation of anomalous values arising from the temporal reconstruction, the effective speed used to determine the engine load factor is capped at 65% of the design speed. For the M/V EVER FAME, this corresponds to 14.95 kn. This cap is a regularisation assumption adopted in this study, rather than a physical or operational upper limit, and does not represent the speed actually sailed by the vessel.

The loading condition is incorporated through a continuous draught factor:

$$f_{draught,i} = \left(\frac{T_i}{T_{max}} \right)^{2/3}$$

where T_i is the draught of the leg and $T_{max} = 14.5$ m the maximum reference draught. The exponent 2/3 is adopted as a parametric assumption of the study rather than as a vessel-specific hydrodynamic calibration. The formulation provides a continuous representation of changes in loading condition instead of relying solely on discrete classifications such as laden, partial and ballast.

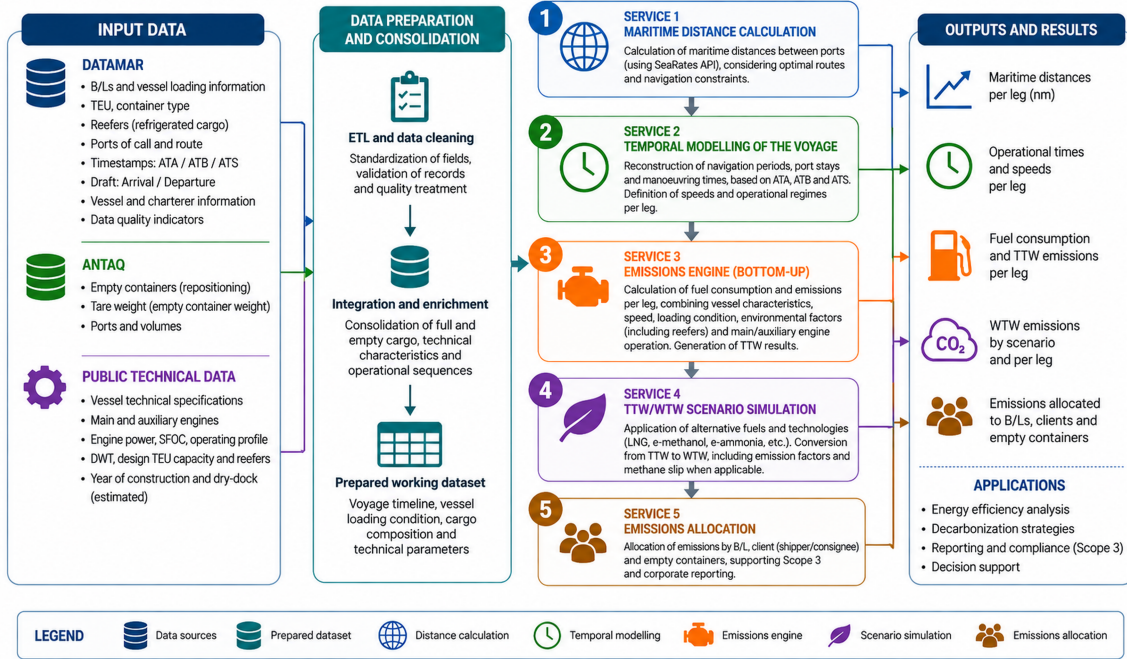


Figure 1: Integrated architecture of the bottom-up approach for the estimation and allocation of maritime emissions.

Main engine consumption is determined from the adjusted power, the sailing time and the SFOC. In the baseline scenario, a constant SFOC of 161 g/kWh is adopted for the MAN B&W 9S90ME-C10 engine, based on the manufacturer’s technical documentation MAN Energy Solutions (2023). This assumption does not incorporate the variation of specific fuel consumption with engine load and, therefore, the results should be read as estimates conditional on the parameterisation adopted.

Additional energy demand comprises the auxiliary engines, the boiler and the refrigerated containers. In the absence of vessel-specific auxiliary-load measurements, the PoC adopts sector-based parametric assumptions of 12% of main-engine demand for auxiliary engines while sailing, 8 t/day for baseline auxiliary consumption in port, and 2.5% of main-engine consumption for the boiler. Reefer demand is computed dynamically from the TEU active on each leg, adopting a reference power of 4 kW/TEU, consistent with the IMO CII guidelines (International Maritime Organization, 2021).

The model further incorporates simplified factors for weather conditions ($CF_{weather}$) and hull degradation ($CF_{fouling}$), the latter defined as a function of the estimated interval since the last dry-docking. After aggregating the propulsive and auxiliary components and applying these factors, total consumption is converted into TTW emissions using the conversion factor corresponding to the fuel. For the HFO baseline scenario, the calculation yields operational CO₂ emissions per leg; CH₄, N₂O and upstream emissions are incorporated sep-

arately in the scenario assessment.

3.3 TTW/WTW scenarios and emissions allocation

The decarbonisation assessment considers ten scenarios applied to the same rotation: a reference HFO case; LNG with ME-GI, X-DF and LPDF 4-stroke technologies; fossil methanol; e-methanol; e-ammonia; and counterfactual conditions with HFO at 11, 16 and 23 kn. Wherever applicable, the comparison retains the same operational basis and alters only the parameters related to fuel, propulsion technology or speed.

For alternative fuels, the equivalent consumption is determined on an energy basis:

$$FC_{alt} = FC_{ref} \times \frac{LCV_{ref}}{LCV_{alt}}$$

where FC is the fuel consumption and LCV the corresponding lower calorific value. The values adopted were LCV of 40.2 MJ/kg for HFO, 49.8 MJ/kg for LNG, 19.9 MJ/kg for methanol and e-methanol, and 18.6 MJ/kg for e-ammonia.

Under the WTW perspective, emissions are computed from the life-cycle greenhouse gas intensity of the fuel (Greenhouse Gas Fuel Intensity, GFI):

$$E_{WTW} = \frac{FC \cdot 10^3 \cdot LCV \cdot GFI}{10^6}$$

where FC is expressed in tonnes, LCV in MJ/kg and GFI in gCO₂eq/MJ. The values adopted are 93.0 gCO₂eq/MJ for HFO; 72.0, 80.0 and 85.0 gCO₂eq/MJ

for LNG ME-GI, X-DF and LPDF 4-stroke respectively; 84.0 gCO₂eq/MJ for fossil methanol; 26.0 gCO₂eq/MJ for e-methanol; and 7.5 gCO₂eq/MJ for e-ammonia.

In the LNG scenarios, the accounting incorporates the effect of methane slip according to engine technology, while the e-ammonia scenario accounts for residual N₂O emissions. These distinctions are necessary because different technologies may exhibit different climate performance even when using the same fuel, as discussed in the literature adopted in the study (Pavlenko et al., 2020; Ushakov et al., 2019). The speed scenarios are treated as counterfactual analyses rather than as pure elasticities between speed and emissions, owing to differences in operational treatment relative to the reconstructed scenario.

Once emissions have been estimated, each shipment record participates exclusively in the legs comprised between its port of loading and its port of discharge. For each leg i , the emission E_i is distributed proportionally among the active records. Under the weight criterion:

$$E_{i,j}^W = E_i \left(\frac{W_{i,j}}{\sum_{k \in A_i} W_{i,k}} \right) \quad (1)$$

and, under the volume criterion:

$$E_{i,j}^{TEU} = E_i \left(\frac{TEU_{i,j}}{\sum_{k \in A_i} TEU_{i,k}} \right) \quad (2)$$

where A_i denotes the set of records active on the leg. The shares attributed to each record are accumulated along the segments comprised between loading and discharge, preserving the distance effectively associated with the respective logistics flow. Empty containers are subjected to the same procedure, allowing part of the operational emissions to be attributed to equipment repositioning.

Mathematical consistency is verified through the conservation principle:

$$\sum_{j \in A_i} E_{i,j} = E_i \quad (3)$$

and, for the complete voyage,

$$\sum_j E_j = \sum_i E_i \quad (4)$$

ensuring that the allocation merely redistributes the emissions computed by the physical-energy model, without creating losses or duplications.

3.4 Plausibility and sensitivity assessment

The assessment of the model combines comparison with external references and sensitivity analyses, and is not to be read as direct empirical validation of the emissions of the M/V EVER FAME. Benchmarks were con-

sidered for daily consumption, emissions per TEU, intensity per TEU·km and the Carbon Intensity Indicator (CII), drawing on technical and scientific references, including (MAN Energy Solutions, 2023), Tran and Lam (2024), Faber et al. (2021) and the IMO CII guidelines (International Maritime Organization, 2021). The comparison checks whether the results lie within orders of magnitude compatible with external references, since independent measurements of fuel consumption or main engine telemetry are not available for the voyage analysed.

Sensitivity to the speed assumptions was additionally examined using an independent sample of 18,728 AIS positions from seven vessels, obtained from the NOAA database (Bureau of Ocean Energy Management and National Oceanic and Atmospheric Administration, s.d.). The comparison indicated a mean difference of +49.9% between the speeds initially used in the development of the model and the median SOG values observed in the sample, which indicated operation predominantly between approximately 60% and 70% of design speed. This analysis was used as an external reference for assessing the plausibility of the parameterisation adopted in the study; it does not establish 65% as an operational upper limit and does not constitute AIS validation specific to the EVER FAME voyage.

Two further sensitivities were considered in interpreting the results. The use of a constant SFOC of 161 g/kWh tends to under-represent efficiency losses at low load; a subsequent assessment with a load-factor-dependent SFOC indicated a potential increase of approximately 8% in total emissions, without this correction being applied retrospectively to the results presented. A separate sensitivity test capped refrigerated demand at the vessel's nominal capacity of 1,400 plugs. This cap is not implemented in the baseline calculation and is evaluated only as a sensitivity case. Its application affects only the BRSSZ-SGSIN leg and reduces total emissions by approximately 1.8%.

At this point it is worth distinguishing plausibility assessment from formal uncertainty quantification. The former, adopted in this study, checks whether the estimates lie within orders of magnitude compatible with external references and examines the sensitivity of the result to critical parameters. The latter propagates probability distributions over the input parameters and reports confidence intervals — a procedure adopted, for example, in AIS-based coastal inventories, which report uncertainty controlled below 6% (Chen et al., 2026), and in multi-scenario transport models coupling optimisation and uncertainty quantification (Hou et al., 2026). The present proof of concept does not undertake this second step, whose incorporation is recorded among the development paths presented in Section 7.

The assessment adopted therefore verifies internal

consistency, external plausibility and sensitivity to the main assumptions, without characterising the results as observed measurements or as empirical validation of the actual consumption of the vessel.

4 Results

Applying the approach to the voyage of the M/V EVER FAME made it possible to reconstruct the sequential physical rotation between South America and Asia and to estimate the operating conditions, fuel consumption and emissions corresponding to the ten consecutive legs. The results presented below correspond to the physical-energy assumptions and to the data defined in Section 3.

4.1 Voyage reconstruction and reference emissions

The spatial reconstruction yielded a total distance of 13,913.3 nautical miles, of which 2,380.2 nm correspond to the five legs of the South American stage and 11,533.1 nm to the five legs between Santos and Ningbo. The Santos–Singapore segment (BRSSZ–SGSIN), at 9,084.0 nm, accounts for approximately 65% of the total distance of the rotation. The temporal reconstruction totalled 1,060.1 h of sailing (44.2 days) and 411.1 h in port (17.1 days), corresponding to approximately 61.3 days of operation.

The implied speeds displayed heterogeneity across legs. In particular, the HKHKG–CNYTN and CNYTN–CNSHA segments returned values of 0.8 and 38.6 kn respectively, associated with limitations of the temporal reconstruction rather than with speeds actually sailed by the vessel. As defined in the methodology, the influence of these values on the propulsive calculation is controlled by the cap applied to the effective speed used in determining the load factor.

Applying the physical-energy model resulted in an estimated total consumption of 3,407.9 t of fuel and emissions of 10,612 tCO₂ TTW. Considering HFO and its life-cycle GHG intensity, the corresponding emission was estimated at 12,741 tCO₂eq WTW.

The distribution of emissions was heavily concentrated on the ocean crossing. The BRSSZ–SGSIN leg accounted for 2,547.0 t of fuel and 7,931.2 tCO₂, equivalent to approximately 74.7% of the TTW emissions of the voyage. The SGSIN–HKHKG leg accounted for 853.4 tCO₂, while the remaining segments made individually smaller contributions.

Estimated average consumption was 56.2 t/day while sailing and 21.9 t/day during port stays. Considering the logistics flows, emissions correspond to 768 kgCO₂/TEU when laden and empty containers are counted together and to 986 kgCO₂/TEU when the denominator is restricted to laden cargo. The mass-based intensity was 92.1 kgCO₂/t, while the indicator based on leg-by-leg transport work returned 37.0 gCO₂/TEU·km.

Table 1: Main results of the reference voyage.

Indicator	Result
Total distance	13,913.3 nm
Sailing time	1,060.1 h / 44.2 days
Port time	411.1 h / 17.1 days
Total fuel consumption	3,407.9 t
TTW emissions	10,612 tCO ₂
WTW emissions	12,741 tCO ₂ eq
Average consumption at sea	56.2 t/day
Average consumption in port	21.9 t/day
Intensity — laden + empty	768 kgCO ₂ /TEU
Intensity — laden cargo	986 kgCO ₂ /TEU
Mass-based intensity	92.1 kgCO ₂ /t
Transport-work intensity	37.0 gCO ₂ /TEU·km

Source: prepared by the authors (2026).

The two legs associated with the main temporal anomalies together account for approximately 412 tCO₂, or 3.9% of total emissions, while 74.7% remain concentrated on the BRSSZ–SGSIN leg, whose implied speed was 14.6 kn. The results should be read under the parameterisation adopted, particularly the constant SFOC of 161 g/kWh; accordingly, 10,612 tCO₂ represents a model estimate and not a direct measurement of the emissions of the vessel.

4.2 Decarbonisation scenarios

The comparison of the ten scenarios reveals differences between the TTW and WTW perspectives. In the reference scenario, based on HFO and an equivalent average speed of 13.1 kn, emissions of 10,612 tCO₂ TTW and 12,741 tCO₂eq WTW were estimated, with a fuel cost of approximately US\$ 1.36 million.

Among the LNG configurations, ME-GI delivered a reduction of 27.2% in TTW and 22.6% in WTW, while X-DF delivered reductions of 10.1% and 14.0% respectively. For LPDF 4-stroke, the reductions were 0.8% in TTW and 8.6% in WTW. The same fuel therefore exhibited significant differences depending on the technological configuration and on methane slip.

Fossil methanol delivered reductions of 10.8% TTW and 9.7% WTW. E-methanol retained the same TTW emission of 9,466 tCO₂eq but returned 3,562 tCO₂eq WTW, equivalent to a 72.0% reduction relative to the reference. E-ammonia returned the lowest result among the scenarios assessed: 125 tCO₂eq TTW and 1,028 tCO₂eq WTW, corresponding to reductions of 98.8% and 91.9% respectively.

Figure 2 makes the difference between the TTW and WTW boundaries particularly evident. For e-methanol, for instance, the TTW reduction is 10.8%, whereas the WTW reduction reaches 72.0%. In the LNG configurations, the result varies with engine technology and methane slip, which is accounted for within the TTW

Table 2: Comparison of the energy and operational scenarios.

Scenario	Fuel	Speed (kn)	TTW (tCO ₂ eq)	Δ TTW (%)	WTW (tCO ₂ eq)	Δ WTW (%)	GFI (gCO ₂ eq/MJ)	Cost (US\$)
HFO reference	HFO	13.1	10,612	—	12,741	—	93.0	1,363,156
LNG ME-GI	LNG	13.1	7,723	−27.2	9,864	−22.6	72.0	1,100,372
LNG X-DF	LNG	13.1	9,543	−10.1	10,960	−14.0	80.0	1,100,372
LNG LPDF 4-stroke	LNG	13.1	10,532	−0.8	11,645	−8.6	85.0	1,100,372
Fossil methanol	MeOH	13.1	9,466	−10.8	11,508	−9.7	84.0	2,581,605
e-Methanol	e-MeOH	13.1	9,466	−10.8	3,562	−72.0	26.0	7,916,922
e-Ammonia	e-NH ₃	13.1	125	−98.8	1,028	−91.9	7.5	9,943,344
Ultra-slow steaming	HFO	11.0	9,896	−6.8	11,881	−6.8	93.0	1,271,132
16 kn speed	HFO	16.0	12,544	+18.2	15,060	+18.2	93.0	1,611,244
Fast steaming	HFO	23.0	19,997	+88.4	24,008	+88.4	93.0	2,568,604

Source: prepared by the authors (2026). In the LNG scenarios, TTW emissions include methane slip specific to the engine technology; for e-ammonia, they include residual N₂O emissions. The variations in the speed scenarios are relative to the reference scenario and do not represent pure speed elasticities.

emissions and consequently contributes to the corresponding WTW results.

The speed scenarios showed a reduction of 6.8% at 11 kn and increases of 18.2% at 16 kn and 88.4% at 23 kn relative to the published reference. Since these scenarios do not fully reproduce the operational cap applied to the baseline scenario, the percentages should not be read as pure speed elasticities. In a homogeneous comparison without that cap, the variations correspond to approximately −15.5%, +7.2% and +70.8% respectively.

4.3 Shipment-level emission allocation

The allocation procedure distributed the voyage emissions across 3,251 shipment records, corresponding to 3,229 laden-cargo B/Ls and 22 aggregated empty-container records. The sum of the attributed shares reproduced the same 10,612 tCO₂ estimated by the model for the voyage, with a conservation deviation of 0.0000%.

The distribution of emissions at B/L level was asymmetric, dominated by records associated with smaller individual emissions and with a small share exhibiting higher values as a function of the volume carried and of the distance between loading and discharge.

At the aggregate level, 983 entities were identified, corresponding to 982 exporters and one aggregated empty-container category. The 20 largest participants concentrate approximately 26.0% of the allocated emissions.

Taken together, the allocation preserves the emissions balance of the voyage and allows the result to be decomposed from the complete rotation down to individual shipment records, maintaining traceability between the emissions estimated by the physical–energy model and the transport flows.

5 Discussion

The results confirm that bottom-up estimation of maritime emissions depends not only on the physical–energy formulation but also on the capacity to represent adequately the operational state of the vessel along the voyage. Integrating commercial, port and technical data made it possible to establish an analytical chain linking route, operating condition, energy demand, fuel, emissions and logistics flows. In this sense, the main contribution of the study lies not merely in the absolute value estimated for the voyage, but in the integration of these different dimensions within a traceable structure.

5.1 Sensitivity to operational data

Among the operational variables, speed exerts a particularly relevant influence owing to the non-linear relationship between speed and propulsion demand, widely recognised in vessel performance modelling (Bialystocki and Konovessis, 2016; Psaraftis and Lagouvardou, 2023). In the present study, however, speeds were reconstructed from the ratio between maritime distance and the time elapsed between port calls and therefore do not constitute direct observations of Speed Over Ground (SOG). Waiting periods, anchorage or differences in temporal granularity may be embedded in the timestamps, making the quality of the temporal reconstruction a relevant source of uncertainty.

The complementary comparison with 18,728 AIS positions from seven vessels identified a mean difference of 49.9% between the speeds considered during the development of the model and the median SOG values observed. This result does not constitute validation of the M/V EVER FAME voyage, but it reinforces the sensitivity of bottom-up models to the representation of speed. The use of higher-resolution AIS may reduce part of this uncertainty, although its application also depends on the quality, frequency and completeness of the avail-

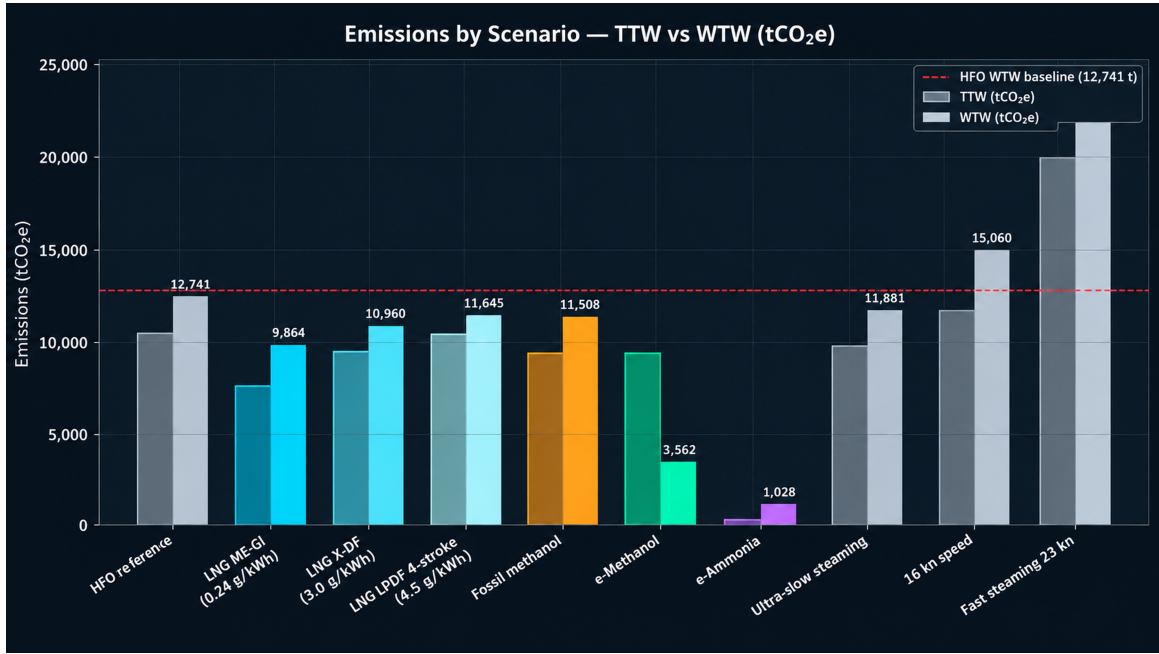


Figure 2: TTW and WTW emissions across the energy and operational scenarios.

able records (emLab and Global Fishing Watch, 2026; Chen and Yang, 2024). The AIS sample is explicitly characterised as an external plausibility reference and not as direct validation.

Other parameters exhibited sensitivities of differing magnitude. The use of a constant SFOC of 161 g/kWh simplifies the relationship between engine load and energy efficiency. The analysis with a load-factor-dependent SFOC curve indicated that the emission estimate could rise from approximately 10.6 to 11.5 ktCO₂, a variation of the order of 8%. This correction was not applied retrospectively to the baseline result, but it indicates that representing engine efficiency at low load may be material to the estimation.

The cargo profile constitutes a further source of sensitivity. Reefers account for approximately 14% of laden TEU, yet the reconstructed LoadProfile may exhibit overlapping records and should not be read as simultaneous physical occupancy of the vessel. When the number of reefers is capped at the nominal capacity of 1,400 plugs, total emissions fall by approximately 1.8%, indicating an aggregate effect smaller than that observed for SFOC, though relevant to the representation of auxiliary demand.

These results reinforce a central aspect of bottom-up modelling: greater mathematical sophistication does not remove the dependence on consistent operational data. Speed, loading condition, engine efficiency, auxiliary loads and environmental conditions interact in determining consumption, so that refining the estimation depends progressively on replacing assumed or reconstructed parameters with observations specific to the

voyage and the vessel. This conclusion is aligned with the literature highlighting the influence of off-design conditions, draught, fouling and environmental factors on energy performance (Borén et al., 2023; Cepowski and Drozd, 2023; Pennino and Scamardella, 2022).

5.2 Life-cycle implications for decarbonisation

The comparison of scenarios demonstrates that an assessment restricted to the TTW perspective may produce an incomplete interpretation of the decarbonisation potential of marine fuels. The WTW boundary alters the relative performance of the alternatives by incorporating emissions associated with fuel production, processing and supply, an aspect of particular relevance for LNG and synthetic fuels (International Maritime Organization, 2024).

In the case of LNG, the results show that the fuel cannot be assessed independently of engine technology. The WTW reduction ranges from 22.6% for ME-GI to 8.6% for LPDF 4-stroke, a difference of approximately 14 percentage points using the same energy carrier. This behaviour stems primarily from differences in methane slip between high- and low-pressure architectures and is consistent with the literature identifying unburned methane emissions as a critical variable for the climate performance of LNG (Pavlenko et al., 2020; Ushakov et al., 2019). The result therefore reinforces that classifying a fuel as a lower-carbon alternative without specifying the technology used may conceal significant performance differences.

The origin of the fuel proved equally decisive. Fossil methanol delivered a WTW reduction limited to 9.7%,

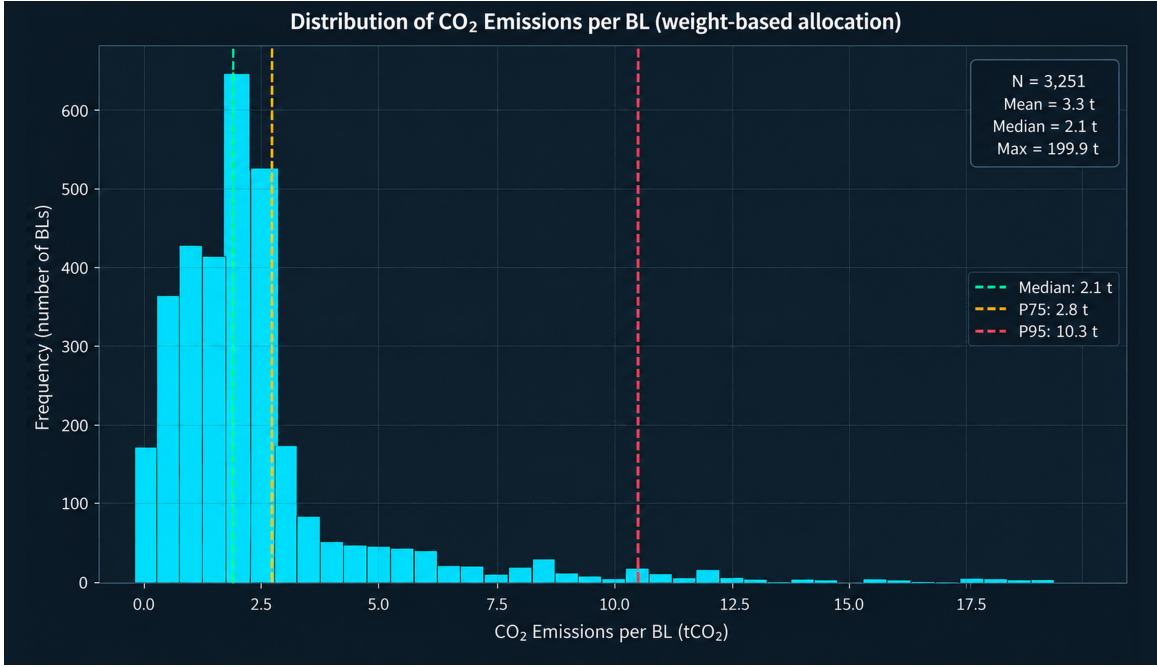


Figure 3: Distribution of emissions between laden cargo and empty containers.

whereas e-methanol reached 72.0%, even though both exhibit the same TTW emission in the model. E-ammonia delivered the largest WTW reduction, 91.9%, retaining a residual TTW emission owing to the N₂O accounted for. These results reinforce the importance of distinguishing emissions produced on board from the GHG intensity associated with the life cycle of the fuel, particularly for synthetic fuels (Bayraktar et al., 2026; Kanchiralla et al., 2024). Other biofuel pathways, including B100 and bioethanol, are also relevant candidates for future application of the proposed framework, although their quantitative assessment would require pathway-specific life-cycle and technological assumptions.

This finding warrants an additional qualification. The intensity factors adopted in the e-methanol and e-ammonia scenarios are catalogue values and should be read as representative of an average production pathway, not as intrinsic properties of these energy carriers. Life-cycle assessments that disaggregate production by region show that the Well-to-Wake result for synthetic fuels is governed by the carbon intensity of the electricity mix used in their synthesis, so that regions with a low-intensity mix — Brazil among them — yield WTW factors substantially lower than those of pathways based on carbon-intensive grids (Lucas et al., 2025). For a route originating in Brazil, this regional dependence is particularly relevant, since it links the decarbonisation potential of the voyage not only to the choice of energy carrier but also to the location of its production and to the availability of national bunkering infrastructure (DNV, 2026; Pacto Global da ONU – Rede Brasil, 2024). Quantita-

tive assessment of these regionalised factors falls outside the scope of this proof of concept.

The climate superiority observed for e-fuels does not, however, automatically imply economic superiority. Under the prices adopted, fuel cost rose from approximately US\$ 1.36 million in the HFO scenario to US\$ 7.92 million with e-methanol and US\$ 9.94 million with e-ammonia. These figures represent fuel cost alone and do not incorporate CAPEX, vessel conversion, storage, availability or bunkering infrastructure. The results therefore identify a trade-off between decarbonisation intensity and energy cost, but do not constitute a total cost analysis.

Taken together, these results indicate that the comparison between low-carbon maritime alternatives must simultaneously consider energy origin, propulsion technology, TTW and WTW emissions and operating conditions. The unit of analysis thus ceases to be the fuel alone and becomes the integrated fuel–technology–operation configuration.

5.3 From vessel emissions to supply-chain carbon

Allocating emissions across 3,251 shipment records while fully preserving the 10,612 tCO₂ estimated for the voyage, with a conservation deviation of 0.0000%, represents a second dimension of the study’s contribution: moving from the aggregated estimation of vessel emissions to their association with the flows that actually used the transport service. This granularity establishes a link between the physical–energy modelling and the commercial structure of the logistics chain.

Consolidating the records yielded 982 identified ex-

porters, in addition to the aggregated empty-container category, with the 20 largest participants concentrating approximately 26.0% of allocated emissions. The distribution indicates that the carbon footprint of the voyage is not associated exclusively with the largest shippers, but is spread across a broad base of commercial flows. This makes it possible to shift the unit of analysis from “how much the ship emitted” to “how the emissions of the operation can be attributed to the logistics flows that took part in it”.

The attribution of emissions to individual shipments carried on the same vehicle is the subject of a dedicated standard. ISO 14083:2023 (International Organization for Standardization, 2023) establishes principles and methods for the quantification and reporting of GHG emissions from transport chain operations, including allocation rules between shipments and the treatment of empty legs, and is operationalised by the GLEC Framework (Smart Freight Centre, 2023). This framework is today the market reference for computing logistics emissions: commercial calculators widely used by shippers declare adherence to the GLEC and alignment with ISO 14083:2023 (A.P. Møller – Mærsk A/S, 2026), relying on methodological engines that combine bottom-up and top-down approaches according to the availability of operational data (Anthes et al., 2026). The two allocation criteria adopted in this study — by mass carried and by TEU — therefore lie within the space of options foreseen by that standard, and presenting them jointly, rather than selecting a single criterion, makes explicit to the reader the effect of the apportionment rule on the result attributed to each shipment record.

The practical usefulness of this attribution nevertheless depends on its verifiability. On the regulatory side, the discussion on the recognition of sustainable fuel certification schemes under the NZF has focused precisely on traceability requirements and on chain-of-custody models capable of ensuring transparency and avoiding double counting (International Maritime Organization, 2026). On the corporate governance side, the literature records that the adoption of digital technologies in the maritime sector coexists with the risk of symbolic disclosure and greenwashing, which shifts the value of information from its existence to its auditability (Qi et al., 2026). In this context, the mathematical conservation verified in the allocation and the preservation of the distinction between observed data, derived variables and assumed parameters are necessary — though not sufficient — conditions for the attribution by bill of lading to be submitted to independent verification.

This transition is relevant to corporate inventories. Under the GHG Protocol, emissions associated with transport may fall within upstream or downstream transportation and distribution categories, depending on the position of the organisation in the value chain, on the

contracting of the service and on the boundaries defined for the inventory. Allocation by B/L and entity may therefore provide supporting information for the measurement of Scope 3 emissions, without in itself determining accounting responsibility for those emissions, which remains dependent on the specific boundaries of each inventory (Greenhouse Gas Protocol, 2011).

The inclusion of empty containers is methodologically relevant in this context. Although they account for approximately 22% of the TEU considered, the 3,057 empty TEU receive 4.7% of emissions under weight-based allocation. Excluding them would not eliminate the energy consumption associated with repositioning, but would implicitly transfer that share to commercial cargo and alter the normalised indicators. Considering this flow explicitly makes the allocation boundary more transparent.

The methodological contribution of the approach therefore lies in connecting two levels that are frequently treated separately: the energy performance of the vessel and the carbon footprint of logistics flows. By combining operational reconstruction, physical-energy modelling, TTW/WTW assessment and conservative allocation, the structure sits at the meso-level resolution characterised in Section 2 — an intermediate position between aggregated methods based on average factors and high-resolution models dependent on continuous telemetry and AIS — taking the leg between port calls, rather than the instantaneous position or the fleet, as the unit of calculation. This feature may be particularly useful where complete on-board data are unavailable but sufficient commercial and port information exists to reconstruct a relevant part of the operation.

The value of the approach thus extends beyond the mere quantification of the CO₂ emissions of a specific voyage, in that it establishes an integrated and traceable chain relating operation → energy → emissions → logistics flow, allowing assumptions and results to be examined at different levels of granularity. At the same time, the sensitivity identified for speed, SFOC and cargo profile shows that this traceability does not remove the uncertainty associated with the input data; on the contrary, it makes more explicit where future gains in accuracy should be concentrated.

This traceability is not merely an internal quality control: recent literature has termed *traceable inventory* the construction of emission estimates in which each aggregated value remains linked to the observations and assumptions that produced it (Elkafas et al., 2023), while the discussion on maritime data governance has been shifting from availability to the conditions of sharing and verification among actors in the chain (Lim et al., 2026). In the present work, it is this layer that makes it possible to separate explicitly observed variables, derived variables and assumed parameters — a separation that

underpins the interpretation of the results and delimits the reach of the estimates.

6 Limitations

This study should be read in the light of limitations related to the scope of the sample, to data availability and to the simplifications adopted in the model. First, the analysis is restricted to a single vessel and a single voyage of the M/V EVER FAME. The quantitative results therefore cannot be generalised directly to other ship classes, routes or operating conditions without further assessment.

The temporal reconstruction uses operational records of heterogeneous granularity, and certain intervals between departure and arrival may incorporate waiting or anchorage periods. Consequently, the speeds computed represent implied voyage speeds rather than direct observations of Speed Over Ground (SOG). The AIS database used as a complement has limited geographical and sample coverage and does not correspond to the EVER FAME voyage analysed; it was employed as an external reference for plausibility and sensitivity, not as direct empirical validation.

The physical-energy model also incorporates simplifications. The baseline scenario uses a constant SFOC of 161 g/kWh, although engine efficiency varies with load. The sensitivity analysis indicated that using a load-factor-dependent SFOC curve could raise estimated emissions from approximately 10.6 to 11.5 ktCO₂, a variation of the order of 8%; this correction was not applied retrospectively to the results presented. Auxiliary-engine, boiler and reefer loads are likewise represented through sector-based parametric assumptions rather than vessel-specific measurements. In addition, the draught correction uses a parametric 2/3 exponent, weather effects are represented by static factors, the date of the last dry-docking is estimated, and complete hydrostatic and hydrodynamic information specific to the vessel was not available.

The reconstructed LoadProfile should be read as an analytical representation of logistics flows rather than as a simultaneous physical manifest of the vessel. Cargo volumes are aggregated from the TEU values associated with active records rather than from record counts, preserving the mathematical conservation of the emissions allocation. A sensitivity test limiting refrigerated demand to the vessel's nominal capacity produced a variation of approximately 1.8% in total emissions. In the current implementation, a zero reefer load on a leg triggers a conservative fallback to nominal reefer capacity; this condition does not affect the voyage analysed here, since all legs contain positive reefer demand, but should be refined in future implementations.

Finally, direct measurements of fuel consumption, main engine telemetry or complete hydrodynamic per-

formance data specific to the M/V EVER FAME were not available. The results are therefore supported by the internal consistency of the model, the conservation of emissions, the sensitivity analyses and the comparison with external references, but these procedures should not be read as empirical validation of the actual consumption or emissions of the vessel. Future work should extend the analysis to multiple vessels and voyages and progressively incorporate vessel-specific AIS data, on-board telemetry, load-dependent SFOC curves, dynamic meteorological data and hydrodynamic parameters specific to the vessels analysed.

7 Conclusions

This study demonstrated the applicability of a data-driven bottom-up approach for estimating and allocating GHG emissions in container shipping, integrating operational reconstruction of the voyage, physical-energy modelling, TTW/WTW scenario assessment and attribution of emissions to logistics flows. Applied to the M/V EVER FAME along a rotation between the east coast of South America and Asia, the approach established a traceable chain linking vessel operation, energy demand, fuel consumption, emissions and cargo carried.

For the sequential rotation of 13,913.3 nautical miles, the model estimated, under the assumptions adopted, a consumption of 3,407.9 t of fuel, corresponding to 10,612 tCO₂ TTW and 12,741 tCO₂eq WTW. The scenario analysis showed that the climate performance of the alternatives depends not only on the fuel but also on its origin and on the propulsion technology. Among the scenarios assessed, e-methanol and e-ammonia delivered WTW reductions of 72.0% and 91.9% respectively, while LNG performance varied significantly with engine technology and methane slip. These results reinforce the need for life-cycle assessment in order to avoid conclusions based exclusively on emissions produced on board.

Beyond aggregated estimation, the approach made it possible to distribute emissions in full across 3,251 shipment records, preserving the voyage balance with a conservation deviation of 0.0000%. The inclusion of empty container flows and the possibility of aggregation by bill of lading and by entity demonstrate the capacity of the method to connect vessel emissions to the underlying logistics structure, broadening its applicability to carbon footprint analysis and to supporting the measurement of value-chain emissions.

The results further showed that the reliability of bottom-up models is conditioned by the quality and granularity of operational data. Speed, SFOC, cargo profile and auxiliary demand exhibited different levels of sensitivity, indicating that greater model sophistication does not replace the need for representative operational observations. The results obtained should therefore be read as estimates conditional on the assumptions and

data available, and not as measurements or empirical validation of the actual emissions of the M/V EVER FAME.

In summary, the main contribution of the study is to demonstrate the feasibility of an integrated structure capable of connecting operational data → energy–emission modelling → assessment of decarbonisation alternatives → granular allocation of emissions, preserving traceability and conservation throughout the process. Extension to multiple vessels and voyages, together with the incorporation of vessel-specific AIS, on-board telemetry and more representative energy and hydrodynamic parameters, constitutes the next step in assessing the robustness and generalisation of the approach.

Three complementary fronts deserve mention. The first is the incorporation of onboard carbon capture technologies into the decarbonisation pathways assessed, already formalised in bottom-up frameworks applied to maritime corridors (Wang et al., 2026b) and the subject of techno-economic assessment in integrated architectures for CO₂ liquefaction and energy recovery (Díaz-Secades et al., 2026). The second is the integration of the estimation with interoperable maritime data architectures, in which provenance and sharing among actors in the chain are treated as design requirements (Aslam et al., 2020). The third is the articulation between the granular output of the model and collaborative decision processes: the literature on collaborative decision-making shows, in transport sectors of analogous structure, that the value of artificial intelligence support lies less in isolated prediction and more in building a shared evidence base among decision-makers (Geske et al., 2024). The attribution of emissions by bill of lading and by entity, in making explicit the share associated with each participant in the logistics chain, offers precisely that kind of shared basis.

Declarations

Conflict of interest. The authors declare no conflicts of interest.

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