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COMPARATIVE ANALYSIS OF CARBON FOOTPRINT ASSESSMENT METHODOLOGIES WITH APPLICABILITY IN THE PORT OF CONSTANTA

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ABSTRACT: The assessment of carbon footprints has become a critical tool for evaluating and mitigating the environmental impacts of various industries. Ports, as complex logistics hubs, contribute significantly to global greenhouse gas emissions, making the implementation of effective carbon management practices essential. This study conducts a comparative analysis of carbon footprint assessment methodologies, focusing on their applicability to the Port of Constanta, one of the largest and most important ports in the Black Sea region. The paper examines different approaches to carbon footprint assessment, including direct emission measurement, life cycle assessment, and input-output analysis, evaluating their strengths, limitations, and suitability in the specific context of port operations. Furthermore, the study highlights how these methodologies can be adapted to local conditions, port infrastructure, and regulatory frameworks, offering a roadmap for improving sustainability and reducing emissions in port management. The findings of this research aim to provide actionable insights for policymakers, port authorities, and environmental researchers in the development of robust carbon footprint assessment tools tailored to port operations.
KEYWORDS: Carbon footprint, port sustainability, greenhouse gas emissions, emission reduction, GHG Protocol

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1. INTRODUCTION

Climate change represents one of the most pressing global challenges of the 21st century, with greenhouse gas (GHG) emissions being the primary driver of global warming. As global trade continues to expand, maritime transport and port operations have become increasingly significant contributors to anthropogenic emissions. Ports, in particular, function as complex, multimodal logistics hubs where a wide array of activities, ranging from cargo handling and vessel traffic to inland transportation and energy use, generate substantial carbon emissions. Accordingly, accurate and context-sensitive carbon footprint assessment within ports is critical for supporting decarbonization strategies and sustainable development.

In recent years, a growing number of carbon footprint assessment methodologies have been developed and implemented across various sectors. These methodologies vary significantly in terms of scope, data requirements, analytical complexity, and applicability to specific industrial contexts. While direct emission measurement techniques offer high precision, they are often resource-intensive. Life cycle assessment (LCA) methods provide a comprehensive perspective but may present challenges related to data availability and boundary definition. Input-output (I-O) analysis, on the other hand, offers a macroeconomic view of emissions but can lack the granularity needed for operational decision-making at the port level.

This paper aims to conduct a comparative analysis of major carbon footprint assessment methodologies and evaluate their applicability within the specific operational and infrastructural context of the Port of Constanta, one of the largest seaports in the Black Sea region. By analysing the strengths and limitations of each method, the study seeks to determine which approaches are most appropriate for assessing and managing emissions in port environments similar to Constanta.

The research contributes to the growing body of literature on environmental performance in port operations and provides actionable insights for policymakers, port authorities, and sustainability practitioners. Ultimately, the study aspires to support the development of more robust, adaptable, and context-aware carbon footprint assessment tools tailored to the needs of maritime logistics and port governance [1].

2. LITERATURE REVIEW

The quantification and management of carbon emissions have become central to contemporary sustainability practices, particularly in carbon-intensive sectors such as transportation and logistics. A carbon footprint is generally defined as the total amount of greenhouse gases emitted directly or indirectly by a process, organization, or product, typically expressed in carbon dioxide equivalents (CO_2e). Numerous methodological frameworks have emerged to assess carbon footprints, with varying degrees of complexity, precision, and applicability across sectors.

Among the most widely adopted approaches is the Direct Emissions Measurement method [2], which involves quantifying emissions from identifiable sources, such as machinery, vehicles, or buildings, through the use of emission factors or real-time monitoring technologies. While this method offers high accuracy, it often requires substantial data collection infrastructure and may not account for indirect emissions from supply chains or external stakeholders.

The Life Cycle Assessment (LCA) approach [3], grounded in ISO 14040 and ISO 14044 standards, provides a holistic view of environmental impacts by evaluating emissions across all stages of a product's or process's life cycle - from raw material extraction and manufacturing to end-of-life disposal. LCA is praised for its comprehensiveness, yet criticized for its methodological complexity and high data demands, particularly in large-scale, diversified environments like ports.

Another prominent framework is the Input-Output (I-O) Analysis [4], which relies on economic input-output tables to estimate emissions associated with monetary flows between sectors. This top-down method is advantageous for national or regional level assessments and for capturing indirect emissions, but it lacks the granularity needed for site-specific operational decision-making.

Recent studies have applied these methodologies in port contexts, including major European and Asian ports, to evaluate emissions from ship operations, cargo handling equipment, terminal activities, and hinterland transport. For instance, the Port of Rotterdam has integrated LCA tools to map emissions across logistics chains, while the Port of Singapore has utilized hybrid approaches combining direct measurement and I-O analysis. However, little research has been conducted specifically on the Port of Constanta, which presents a unique case due to its geographical location, infrastructure profile, and regulatory landscape.

The literature suggests [5] that no single methodology is universally superior; rather, the choice depends on contextual factors such as data availability, the scope of analysis, technical capacity, and the desired level of precision. This review highlights the need for a tailored, context-sensitive approach to carbon footprint assessment in port environments, an approach that this study aims to explore.

3. METHODOLOGY

This study uses a comparative, qualitative approach to analyse three carbon footprint assessment methods: Direct Emissions Measurement, Life Cycle Assessment, and Input-Output Analysis, and evaluates their applicability to the Port of Constanta.

3.1 Method selection

Based on the literature and international standards (e.g., GHG Protocol, ISO 14064, ISO 14040), the three main methodologies were selected because of their relevance in transportation and logistics.

3.2 Evaluation criteria

The methods are compared based on six practical criteria:

- Data availability in the port context;
- Method complexity and ease of implementation;
- Accuracy of results;
- Coverage of direct vs. indirect emissions;
- Suitability for decision-making;
- Adaptability to local regulations and port-specific conditions.

3.3 Context analysis: Port of Constanta

The study uses descriptive data and public reports about the Port of Constanta to identify key emission sources, including ships, cargo handling equipment, and electricity usage. The port's operational and regulatory environment is considered when testing how well each method fits local needs.

3.4 Comparative matrix

The findings are organized into a comparison table that highlights the advantages and limitations of each methodology based on the evaluation criteria. This methodology provides clear guidance for selecting a suitable carbon assessment approach for the Port of Constanta or similar port environments with limited resources or complex structures.

4. CASE STUDY: PORT OF CONSTANTA

4.1 Overview of the port

The Port of Constanta [6] is Romania's largest seaport and one of the most important maritime logistics hubs in the Black Sea region. It covers an area of approximately 3,900 hectares, including both land and water surfaces, and features over 150 operational berths. Its strategic position makes it a critical link in regional and international supply chains, serving as a transit hub for goods moving between Europe, Central Asia, and the Middle East.

The port handles a wide variety of cargo, including containers, bulk cargo (such as grain, coal, and fertilizers), petroleum products, and general goods. Its infrastructure includes container terminals, oil and chemical terminals, storage silos, warehouses, shipyards, and industrial processing zones. The port is also integrated with rail and road networks, making it a multimodal transport platform.

4.2 Main sources of emissions

Due to its size and complexity, the Port of Constanta generates emissions from multiple sources, which can be grouped into several categories:

- Vessels: Ships docking at the port produce emissions during manoeuvring, loading/unloading, and while berthed. Auxiliary engines and fuel combustion contribute to significant Scope 3 emissions.
- Cargo handling equipment: cranes, forklifts, reach stackers, and other diesel-powered machinery produce direct (Scope 1) emissions during daily operations.
- Road transport: Trucks and other vehicles moving goods to and from the port terminals are responsible for a large share of CO_2 emissions, particularly due to traffic congestion and idling.
- Buildings and infrastructure: Port offices, warehouses, and lighting systems consume electricity, resulting in Scope 2 emissions linked to energy use.
- Industrial and tenant activities: Many operations in the port are carried out by private tenants who run fuel depots, storage facilities, and repair services, each contributing indirectly to the total footprint.

Because of this diversity, applying a single carbon assessment method may not fully capture the complexity of emissions sources.

4.3 Regulatory and policy context

The Port of Constanta operates under a combination of national and European Union environmental regulations. Romania's national climate policies are aligned with the EU's Green Deal objectives and the EU Emissions Trading System (EU ETS), which applies to major emitters in maritime and industrial sectors. In addition, port operations are indirectly influenced by international maritime regulations such as MARPOL Annex VI, which sets limits on emissions from ships (e.g., sulphur oxides and nitrogen oxides). These regulations create pressure on port authorities to monitor and reduce emissions not only from their own assets but also from tenant operations and vessel activities [7].

Despite growing attention to environmental compliance, emissions reporting in the port remains fragmented, particularly due to the mixed public-private management structure. This makes it difficult to apply certain carbon assessment methodologies unless adapted to the local operational reality.

5. COMPARATIVE ANALYSIS OF ASSESSMENT METHODOLOGIES

In this section, the three selected carbon footprint assessment methodologies: Direct Emissions Measurement, Life Cycle Assessment (LCA), and Input-Output (I-O) Analysis, are compared in terms of their practicality and relevance to port operations, using the context of the Port of Constanta as a reference point.

5.1 Evaluation Criteria

- Data availability – Can the method work with the type of data typically available in ports like Constanta?
- Ease of implementation – How difficult is it to apply the method in a port setting?
- Accuracy of results – How precise and reliable are the emission estimates?
- Scope of coverage – Does the method cover direct (Scope 1), indirect energy (Scope 2), and supply chain emissions (Scope 3)?
- Decision-making value – Can the results inform operational or strategic decisions?
- Adaptability to local context – Can the method be tailored to the regulatory and infrastructural reality of the Port of Constanta?

5.2 Comparative analysis

Figure 1 and Table 1 show a comparison matrix of the three methodologies analysed based on the evaluation criteria, limitations, strengths and applicability to the present case.

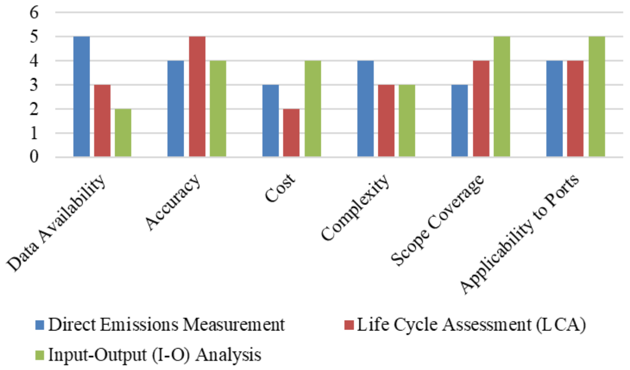

Figure 1. Comparative analysis of carbon footprint assessment methodologies

The key findings are the following:

- Direct Emissions Measurement is useful for activities controlled directly by the port authority (e.g., fuel use in port vehicles or cranes), but its usefulness is limited when data must be collected from independent operators or shipping companies. It is best used for real-time, operational control in Scope 1.

Table 1. Comparative matrix of the three methodologies

Methodology	Strengths	Limitations	Applicability to Constanta Port
Direct Emissions Measurement	- High precision for on-site sources - Useful for Scope 1 emissions	- requires monitoring equipment - limited coverage of Scope 3 emissions	Moderate: works well for port-owned assets but less for tenant activities
Life Cycle Assessment (LCA)	- comprehensive (Scope 1–3) - standardized (ISO 14040/44)	- data-intensive - methodologically complex	High: Suitable for infrastructure-wide analysis, including logistics flows
Input-Output (I-O) Analysis	- useful for indirect emissions - works with economic data	- low granularity - based on generalized emission factors	Low to Moderate: Applicable only for high-level estimates, not operational insights

- Life Cycle Assessment provides the most complete picture of emissions across the port's supply chain, including upstream and downstream processes. However, it requires significant data input and technical expertise. For a port as Constanta, with diverse infrastructure and mixed operations, LCA is ideal for strategic planning, especially if applied in stages or with external consultancy support.
- Input-Output Analysis is suited for understanding the broader economic impact of port operations, particularly when detailed operational data is unavailable. It may serve as a preliminary tool for estimating emissions from port-related economic activities but is too general for targeted emission reduction planning.

Based on the characteristics of the Port of Constanta and the criteria analysed, the most effective approach would be a hybrid model, combining:

- Direct measurement for easily monitored, high-emission assets (e.g., cranes, vehicles);
- Simplified LCA for infrastructure and logistics chains;
- Optional I-O analysis for macro-level reporting or integration into national GHG inventories.

Such a blended approach would balance practicality, accuracy, and completeness, and could be implemented gradually based on available resources and data access.

6. DISCUSSION

The comparative analysis of carbon footprint assessment methodologies highlights the complexity of applying standard tools in operational environments like ports, where multiple actors, diverse infrastructures, and fragmented data coexist. In the case of the Port of Constanța, these challenges are further amplified by its mixed public-private governance structure and the varied emission sources spread across different terminal operators and logistics services.

One key insight is that no single methodology can provide a complete solution on its own. While Direct Emissions Measurement is valuable for operational control and equipment-level monitoring, it lacks the ability to capture emissions from upstream or downstream activities, particularly those operated by private tenants. On the other hand, Life Cycle Assessment offers broader coverage, including Scope 3 emissions, but it is resource-intensive and may not be feasible to implement across the entire port without phased planning or external support.

Input-Output Analysis, although useful at a macro level, was found to be less practical in the specific case of Constanta, where actionable emission data are needed at the operational level. Nevertheless, it could serve as a useful complementary tool for national or regional policy reporting and for linking port activities with broader economic-environmental models.

Another important observation is the trade-off between accuracy and feasibility. Direct measurement offers precise results but is costly and limited in scope; LCA is methodologically rigorous but requires significant data and expertise; I-O is easier to implement but less specific. These trade-offs must be considered carefully by port authorities when choosing which method to adopt.

Furthermore, the discussion reveals that institutional and regulatory factors play a major role in determining which methods are viable. In the EU context, alignment with regulations such as the EU Emissions Trading System (EU ETS) or upcoming climate reporting obligations under the Corporate Sustainability Reporting Directive (CSRD) makes robust emissions monitoring not only beneficial, but increasingly mandatory.

For a port like Constanta, a phased implementation strategy appears to be the most realistic. This could begin with basic direct measurement for Scope 1 sources, followed by LCA applications for infrastructure projects and long-term sustainability planning. With time, a more integrated emissions management system could be developed, possibly linked to national inventories through simplified I-O models.

Overall, the results suggest that context-sensitive, hybrid approaches are essential in port environments. Method selection should not be rigid, but instead based on operational needs, available data, and long-term sustainability goals.

7. CONCLUSIONS

This study has explored and compared three widely used carbon footprint assessment methodologies: Direct Emissions Measurement, Life Cycle Assessment (LCA), and Input-Output (I-O) Analysis, with a focus on their applicability to port environments, using the Port of Constanta as a case study. The analysis revealed that:

- Ports are complex systems with multiple, decentralized sources of emissions, which makes carbon footprint assessment both necessary and challenging.
- Each methodology offers specific advantages and limitations: direct measurement provides high accuracy for Scope 1 emissions; LCA is comprehensive but resource-intensive; I-O analysis is macro-level and less operationally relevant.
- The Port of Constanta, due to its infrastructure, operational diversity, and regulatory context, would benefit most from a hybrid approach that integrates the strengths of multiple methods.

Additionally, institutional factors, such as EU climate regulations and fragmented port governance, significantly influence the feasibility and impact of each method. Based on the findings, the following recommendations are proposed for the Port of Constanta and similar ports:

- Begin with Direct Emissions Measurement for core port operations and gradually incorporate LCA for infrastructure and logistics processes.
- Create a port-wide data-sharing platform to collect emissions data from all stakeholders, including private terminal operators and service providers.
- Require emissions evaluation as part of new infrastructure projects, using LCA to guide low-carbon investments and energy-efficient technologies.
- Utilize EU Green Deal and climate transition funds to finance technical assessments, digital infrastructure, and capacity building for emissions monitoring.
- Work closely with environmental authorities and industry partners to align port activities with emerging EU sustainability directives such as CSRD and Fit for 55.
- Invest in training and partnerships with universities or consulting firms to build internal expertise in carbon accounting and environmental reporting.

By following these steps, the Port of Constanta can move toward a more sustainable and accountable operational model, while also setting an example for other regional ports in the Black Sea and the wider European maritime network.

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