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Geographical aspects of the logistic carbon footprint: estimating the environmental impact of freight transport

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Abstract

The network of increasing interconnections on a global scale involves a reduction of physical distances, which is reflected in the intensification of the freight flows. Among human activities, transport and logistics are responsible for an important share of pollution and carbon-related emissions. It is therefore clear that the environmental aspects closely linked to the relationship between economic activity and geography, take on an even more central role. Quantifying the emissions produced along different supply chains is a challenging task; carbon-based emissions generated by the logistics sector have a relevant impact on environmental sustainability. We propose an innovative approach to the estimation of the carbon footprint as an indicator of the environmental sustainability of logistics processes. A tool for computing the logistics carbon footprint, which clearly defines the boundaries of application of the model and its scope has been developed. The main sources of emissions were analyzed in detail and then an adjustment factor was introduced to summarize the exogenous factor that are not easily to model. Once the carbon footprint processing method had been framed, this synthetic indicator for the analysis of the environmental sustainability of different logistics processes was used regarding a logistics chain for intra-Mediterranean freight traffic.

Keywords: Carbon Footprint, Logistics, Maritime Transport, Sustainability

1. Introduction

On a daily basis oceans are navigated by a massive fleet of merchant ships (more or less 55,000 cargo ships[1]). This provides the supply of raw materials, semi-finished and finished products from places of origin to target markets along

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[1] Source: https://www.statista.com/statistics/264024/number-of-merchant-ships-worldwide-by-type/.

increasingly fragmented and articulated supply chains. This is reflected in a constant intensification of trade flows (from 4.0 billion in 1990 of tons to 10.6 billion in 2020[2]). Maritime transport represents the geographical expression of the structure of international trade (Vallega, 1997), where ports take on the role of strategic intersection hubs (Vigarié, 1992), emphasizing how maritime transportation takes on a key role within the industrial landscape (Soriani, 2010).

Different transport systems represent an important driver of economic development in an increasingly interconnected and globalized scenario. We must therefore consider how each movement takes into account a specific geographical location, which is linked to spatial flows and their patterns (Rodrigue, 2020). Transport mitigates geographical constraints and plays a key role in sustaining spatial relationships between locations, and is composed of several key components: modes, infrastructure, networks, and flows. It seems clear that geography represents an extremely central element in the analysis of the transport system (Notteboom et al., 2021).

We can therefore see how environmental aspects related to the relationship between economic and geographic processes take on a progressively central role. It is estimated that the shipping sector generates about 3% of total greenhouse gas emissions each year. Analyzing the entire transportation sector, this level rises to 28% (EMEP/EEA, 2019). Hence the need for a careful and concrete assessment of the environmental impact of logistics processes will be examined.

The carbon footprint is a synthetic indicator of direct and indirect greenhouse gas emissions generated by a given process, expressed in terms of CO_2 equivalent (McKinnon, 2018). The climate warming power of different gases is expressed in terms of equivalent carbon dioxide: each gas considered is weighted for its specific contribution to the increase in the greenhouse effect. The Global Warming Potential of a gas can be defined as the total contribution to global warming resulting from the emission of one unit of that gas as compared to one unit of carbon dioxide, which by definition is set equal to 1 (Pernigiotti, 2012).

The paper proposes to develop a tool to calculate the logistic carbon footprint, following a quantitatively correct approach and a harmonized method of evaluation, aimed at obtaining comparable estimates of pollutant emissions for different logistics chains (Franchetti and Apul, 2013). To this aim, consumption and thus emissions from intermodal transport will be outlined, highlighting not only the quantitative aspect but also the uniform approach taken to assess the Carbon Footprint, in order to make the proposed tool standardizable and comparable.

The normative notions that regulate the reporting of the Carbon Footprint are the ISO 14064:2006 standards, later updated in 2019 (International Organization for Standardization, 2018), and the GHG Protocols proposed by the World Resources Institute and the World Business Council for Sustainable Development (WRI and WBCSD, 2007; WRI and WBCSD, 2016). The objective of these normative references is to define common standards for the measurement of the carbon footprint associated with a process.

2. The logistic carbon footprint

The logistic carbon footprint is the synthetic indicator used to quantify all the emissions related to the movement of goods from the production site to the final destination. The idea is to formalize a model capable of defining a standardized approach to calculating the environmental impact of a logistics chain, articulated through various modal shifts. The core of the logistic chain is represented by maritime transport, the leading sector of international trade, while at the top and bottom of this process the movement of freight takes place by different modes of transport: rail and road. Ports represent the fundamental connection points for these processes (Notteboom et al., 2021). The current increasingly globalized and inter-

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[2] UNCTAD, *Review of Maritime Transport 2021*. United Nations publication. Sales No. E.21.11.D.21. New York and Geneva, 2021.

connected macroeconomic scenario (McKinnon, 2010) shows the importance of the impact of the transport system on environmental sustainability.

To evaluate the GHG emissions of a logistic chain, we will have to carry out a preliminary analysis of the main modes of transport used, starting from the different categories of cargo vessels in the shipping sector and then focusing our attention on road and rail traffic. The consideration of these transport modes allows us to focus on a multiscalar geographical approach and to consider the most used means for freight movement. After an initial overview of the vehicles, it will be essential to study the internal combustion engine and the energy required. We can then proceed to calculate the direct and indirect emissions resulting from a logistic process that includes the three modes of transport mentioned above: road, rail and sea.

However, to follow a standardized approach to calculation, an adjustment factor has been introduced to enclose two different incremental launches in the same parameter: the first one of 5% related to the direct emissions and the second one of 2% attributable to indirect emissions. The adjustment factor takes into account all the exogenous factors such as tides, traffic conditions, adverse sea currents, tyre wear and tear, etc., as well as other negligible emission factors. A relevant problem to be dealt with in the study of the carbon footprint is that of discretion: delineating the boundaries within which to elaborate an emissions analysis appears extremely complex. For this reason, the adjustment factors have been set that consider all the emissions not previously accounted by the analysis and the exogenous influencing factors. This approach allows the Carbon Footprint analysis of the supply chain to include only the most relevant and closely related elements of the process (Gallo, 2022). However, all other omitted factors will be considered within a single parameter. The proposed adjustment factor thus becomes fundamental in order to concretely define the boundaries of the calculation model for the evaluation of emissions deriving from a supply chain and to pursue the criteria of comparability and transparency foreseen for the drafting of the carbon footprint, as it smoothes out possible discretions. It is important to highlight that also the handling operations in the various intermodal hubs will be considered within the adjustment factor. This adjustment factor has been obtained by carefully analyzing detailed emissions related to port handling operations (Mazzarino and Braidotti, 2022), where usually over 80% of pollutant emissions derive from ships moored at the quay or maneuvering in the bay area (Saravia de Los Reyes et al., 2020), and then increased to account for all the other factors. Port operations are responsible for between 3% and 5% (Gallo, 2022) of the total emissions produced by a logistics chain. However, the adjustment factor also includes the more complex incremental changes, such as tides, waves, traffic conditions, water viscosity, tyre friction and so on: all these factors have been quantified as 2% of total emissions. From these observations, we decided to consider the increased correction of 7%. We can therefore observe how to quantify the carbon footprint and will consider only the emissions from the dynamic flows, while all the detailed emissions will be accounted for in the adjustment factor.

It is clear that in the logistic environmental impact many factors can have a slight impact on the quantification of emissions. Therefore, it is necessary to clearly define the boundaries of the model within which to calculate the carbon footprint in order to obtain a model that is qualitatively correct and at the same time applicable to different realities.

2.1 Shipping Sector Emissions

To quantify the emissions of the naval segment, we will start from the different types of vessels and the hourly average consumption (as presented in Tables A and B of the appendix) considering two different approaches: the first refers to the actual fuel consumption, considering only engines powered by heavy fuel oil (HFO) and the second is based on the energy used in terms of kWh, able to express the emissions in terms of grams of pollutant per kilowatt-hour.

It is essential to fix some base hypotheses relative to maritime transport:

- engine load at 80% for the main engines during navigation, which is usually the optimal one (IMO, 2020).
- exclusive use of auxiliary engines at 60% of the load factor for the quay and dockside operations.

These assumptions will allow us to quantify the average consumption for the different types of ships in navigation and during port operations.

However, it must be emphasized that fuel consumption during navigation will have to be corrected for the "specific fuel consumption" (SFC)[3] of the heavy fuel oil (HFC) under the assumption of the engine load at 80%. According to this assumption it will be necessary to multiply the consumption by 1.003 to obtain the effective fuel oil burned in the internal combustion engine of the vessels (IMO, 2020).

Once the fuel consumption has been evaluated, it will then be possible to convert it into the volume of greenhouse gases produced (IMO, 2020) as in the Table 1.

The conversion factors presented in the table were defined from the estimates provided by the International Maritime Organization in the Fourth IMO Greenhouse Gas Study (IMO, 2020). In the volume, the main emission factors are presented under two different approaches: the first one relates to carbon dioxide and sulfur sulfide emissions expressed in terms of grams of pollutant per gram of fuel consumed, and the second one relates to nitrogen oxide, methane, carbon monoxide and particulate matter, where emissions are expressed in grams per kilowatt hour, a measure of power demanded by the ship.

Emission Factors:		g pollutant/ g fuel	GWP-100
CO2	Carbon Dioxide	3.114	1
SO2	Sulfur Sulfide	0.05	-
Emission Factors:		g/kWh	
N2O	Nitrogen Oxide	0.03	298
CH4	Methane	0.2	25
CO	Carbon Monoxide	1.04	1.8
PM10	Particulate matter	0.01	-

Table 1. Emission factors for HFO fuel consumption. Source: author's elaboration on "Fourth study of GHG" of IMO 2020 pages: 278-282 and 83[4].

As soon as the emission of the cargo ships is quantified, it is important to weigh each GHG for its global warming potential due to reach the amount of the emissions expressed in terms of CO_2 equivalent.

The last step to the evaluation of ship-side emissions will be to consider the 5% incremental adjustment factor as seen above, thus obtaining emission volumes related not only to cargo shipping but also to handling within port hubs.

2.2 Road transport emissions

To elaborate on the footprint covering the whole logistic chain, the analysis of emissions from road freight transport is essential. In this section, we will define the tools for the evaluation of greenhouse gas emissions from heavy-duty trucks (ISPRA, 2015). For this reason, estimates will be made on an average sample, considering the most used vehicles (Thibault, 2015; McKinnon et al., 2015).

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[3] The specific fuel consumption is obtained using the following equation:
$SFOC_{load}=SFOC_{baseline}*(0.455*load^2-0.71*load+1.28)$
Where $SFOC_{load}$ is the specific fuel oil consumption (SFOC) at a given engine load, $SFOC_{baseline}$ is the lowest SFOC for a given engine. Using the equation for SFOC as a function of engine load, it will be optimized at approximately 80% load (IMO, 2020 pages: 475-480).

To define the diesel consumption of the heavy vehicle fleet mostly used, the “Handbook emission factor for road transport” (HBEFA) has been analyzed: a Microsoft Access database that includes the emissions and fuel consumption for all categories of circulating vehicles, based on a sample of over 50,000 different vehicles.

From an elaboration of this information, Table C in the appendix has been outlined that highlights the volumes of emissions and average consumption for the circulating fleet, divided by weight and characteristics (Suzanne and Lewis, 2019). The information provided thus allows us to calculate the fuel consumption and greenhouse emissions for each route depending on the type of vehicle used (McKinnon et al., 2015; European Commission – DG Climate Action 2019). Once the emissions from the road transport have been quantified, it is important to introduce the adjustment factor of 5% to consider all the exogenous factors (traffic conditions, temperature, weather, climb and others), to obtain the final volume of GHG deriving from road transport.

2.3 Railway emissions

The third mode of transport that we will consider for the quantifications of emissions from the supply chain is rail transport (Office of Rail and Road, 2021). The main indicator for calculating energy and emissions from rail transport comes from the energy consumed based on the net weight of the train (Office of rail and road, 2021). For this analysis, the basic assumption is that in almost all situations, locomotives are powered by electric motors and are used to move goods by rail. As a consequence, direct emissions of greenhouse gases will be insignificant (International Union of Railways, 2016).

For this analysis, we will consider different categories of trains, defined according to their load capacity. The average size of freight trains in Europe is 1,000 tons. To quantify the emissions from the railway sector it will therefore be necessary to analyze the indirect emissions. This set of emissions falls into the energy used to power the electric motors of locomotives (García-Álvarez et al., 2013; EcoTransIt World Initiative, 2019) as presented in Table D of the appendix. For the railway sector, it is possible to estimate the energy consumption in terms of kilowatt-hour per ton per kilometer and consequently the carbon dioxide emissions produced are expressed in kg CO_2 per ton per kilometer as reported in Table D of the appendix. It becomes necessary to further emphasize how greenhouse gas emissions from locomotives powered by an electric engine are defined as indirect emissions, thus generated by the supply of electricity. For rail transport, we will consider both the direct and indirect factors of adjustment of 5% and 2%, to then reach a more precise estimation that includes the geophysical aspect of the terrain, any possible difficulties with the railway line, the use of diesel locomotives for the maneuvering inside the logistic hub borders, and the 2% referred to the supply of the electricity (Schmied and Freid, 2012).

2.4 Indirect emissions

In addition to the direct emissions, the calculation of the Carbon Footprint for the logistics chain also includes indirect emissions (WRI and WBCSD, 2015): the class of emissions that cannot be directly attributed to the production process under analysis, but which derive from activities connected to it. For the logistics chain in particular the emissions will be considered deriving from the supply of the fuel oil used by different modes of transport (McKinnon, 2018).

It will be essential to study the entire life cycle of heavy fuel oil used for the shipping sector and the diesel fuel used for the trucks: from the processes of extraction, processing, refining, storage and final distribution of the fuel, so as to evaluate the indirect emissions of a logistics chain. Generally, this process is called “From Well to Tank” (WTT) (Prussi et al., 2020). The problem to be faced now is to calculate the energy used starting from the extraction of the primary source from the oil well, up to making it available as fuel for the internal combustion engines used within the supply chain. The estimations of the indirect emission based on the study of the Joint

Research Center (Prussi et al., 2020) suggest that for the diesel fuel for heavy-duty trucks the indirect emission will be defined as 818.4 grams of CO_2 for each kilogram of fuel used, instead, regarding the HFO used by vessels, the emissions will be 243.4 grams of CO_2 for each kilogram of fuel.

This information will be indispensable in quantifying the indirect emissions of the entire logistic value chain. Once the equivalent carbon dioxide emitted by the different modes of transport has been calculated, we will therefore introduce the adjustment factor of 2%, to take into account all the distortions caused by the supply of the fuel during the process "from well to tank".

Table 2 is a summary table of the calculation process for the logistic carbon footprint, following the methodological approach previously introduced.

3. Case Study: Carbon footprint of a TEU from Port Said to Hamburg

The approach to the standardized calculation of the logistic carbon footprint was outlined above, highlighting the consumption, emissions and adjustment factors useful in formalizing a calculation tool for the synthetic indicator.

On this information, we will now go on to elaborate a case study considering the transport of a single TEU from Port Said with the logistics hub of Hamburg as its final destination, with an initial modal shift planned at the Port of Trieste (Robiglio, 2010), where the container will be carried by train to the Duisburg Freight Village, and then arrive at its destination by truck with a 25-ton carrying capacity.

The logistics chain will then work through three stages:

- the first phase from Port Said to Trieste, through a container ship with a maximum capacity of 8,000 TEUS and a 90% load factor. We will consider a ship travelling at an estimated average speed of 17.5 knots, with calls of 12 hours at each port considered during the routing.
- in the second phase, a freight train will be considered departing from the Port of Trieste and with its final destination at the Duisburg Freight Village. The convoys assembled within the Port of Trieste reach a maximum length of 480 meters, with a total of 24 wagons and a loading capacity of 48 TEUS.
- instead, the third modal shift will take place at the Duisburg Freight Village, where the TEU under analysis will be loaded onto a truck to reach its final destination at the container terminal of Hamburg.

The geographical visualization of the sea and land route followed for the different modes of transportation is presented in Figure 1.

Once the logistics chain has been defined, we will now proceed to quantify the emission volumes expressed in terms of CO_2 equivalent, following the approach to calculation examined above, thus starting with the shipping route followed by the container ship (Table 3).

To quantify the emissions produced in the context of maritime transport we will need to follow the two different approaches analyzed above: the first one relates to average hourly consumption, which is 3.27 tons per hour at sea for 186 hours of travel time and 0.38 tons at the dock to be multiplied by the 6 calls of 12 hours. Instead, the second approach refers to the kilowatt-hours generated by the engine, which under the assumption of an 80% optimal engine load, that reaches 44,183 kilowatt hour: that is the average engine power between the 5,000-7,999 and the 8,000-11,999 container ship class under the optimal load assumption. The hourly HFO consumption for the route under analysis could be multiplying the hours of navigation. For each port of call, we can estimate the fuel consumption as 0.38 tons per hour multiplied by 12 hours at the dockside per each port and for the 6 different calls.

	Direct Emission	Indirect Emission	Total Emission
Cargo Vessel	Following a double approach on engine power and HFO consumption, to find the volume of emissions in terms of CO_2 equivalent. Then consider in the quantification the adjustment factor of 5%	Knowing the fuel consumption, to take into account the indirect emission from the supply chain of HFO, each kilogram of fuel will produce 243.4 grams of CO_2 equivalent. Then we will consider the adjustment factor of 2%.	The sum of direct and indirect emissions for cargo vessel route
Freight Train	-		The emissions for rail traffic are related to the energy supply: the main data to use for the environmental footprint of the railway sector is that 22.8 grams of pollutant will be produced for each ton per kilometer moved. Having defined the emissions, we will finally include the adjustment factor of 7%.
Heavy Trucks	Using the information from the HBEFA related to the road sector, we can estimate the fuel consumption and the GHG of the road transport by heavy-duty trucks. We can then consider the incrementation adjustment factor of 5%	Once the fuel consumption has been found, it is possible to quantify the indirect emissions for the supply of the fuel for the process “From well to the tank”, under the assumption that, each kilogram of gasoline will produce 818.4 grams of CO_2 equivalent. Then we will consider the adjustment factor of 2%	Sum of the direct and indirect emissions for road transport.
			Logistic carbon footprint indicator: the sum for all the direct and indirect emissions for the different modes of transport.

Table 2. Summary table of the Logistic Carbon Footprint calculation tool.
Source: author’s elaboration based on the proposed calculation methodology.

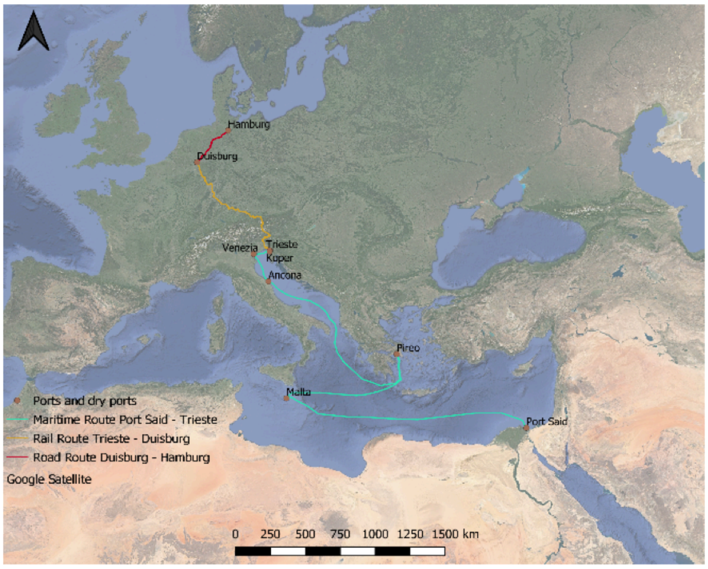

Figure 1. Sample of transport route Port Said – Hamburg. Source: author’s elaboration from selected sources https://ss.shipmentlink.com, www.evergreen-line.com and https://www.vesselfinder.com, https://www.ecotransit.org.

Mediterranean Route			
Origin	Destination	Transit Time (Hours)	Distance (NM)
Port Said	Malta	62	959
Malta	Pireo	45	697
Pireo	Ancona	66	1,024
Ancona	Venezia	8	127
Venezia	Koper	4	63
Koper	Trieste	1	12

Table 3. Route Port Said – Port of Trieste.
Source: author's elaboration[5].

It is possible to quantify the fuel consumption as 608.22 tons for the navigation route and 27.36 tons at quay side.

Once the total amount of fuel has been adjusted for the SFC of 1.003, it is possible to quantify the total consumption of 637.5 tons of heavy fuel oil (HFO). Hence, it will be possible to calculate the total amount of emissions based on the emission factors previously presented. This shows that the direct emissions attributable to the shipping segment will be 2,147.1 tons of CO2 equivalent. Considering the emission intensity for a single TEU of 8,000 TEUS containership with a load factor of 90%, each container will be responsible for 298.2 kg of carbon dioxide equivalent. At this point, it will be imperative to consider the 5% incremental adjustment factor to include all omitted and exogenous factors in the calculation as well. The total direct emissions for the Port Said - Port of Trieste route will be 313.1 kg of CO2 equivalent per TEU.

We will now proceed to calculate the indirect component of emissions of the "from well to tank" process, where we know that for every kg of HFO consumed, 243.4 grams of CO2 equivalent will be produced. This data will then be corrected for the adjustment factor of 2%. In this way, the indirect emissions per single container can be quantified as 21.9 kg of CO2 equivalent.

Once the modal shift has taken place within the Port of Trieste, the container will depart with Duisburg Freight Village as its destination. The assembled train will have a total weight capacity of 1,098 tons, divided into 48 TEUS of 20 tons and an electric locomotive of 138. This information will be useful in estimating energy consumption first and thus emissions from rail transport. The estimated energy consumption for rail transport is 1.1 kilowatts per ton per kilometer while the emissions of 22.8 grams of carbon dioxide equivalent per tons per kilometer. Thus, knowing the travel distance of 1,182 kilometers that divides the place of departure to the interchange logistics hub at Duisburg, we can quantify the estimated emissions as 29.59 tons of CO2 equivalent, which per single TEU is 616.5 kg.

The 7% overall adjustment factor for the rail sector will now be considered. The evaluation of this adjustment factor is equal to 43.1 kg. In conclusion, we can therefore state that the emissions for rail transport are equal to 659.6 kg of CO2 equivalent of pertinence to indirect emissions (García-Álvarez et al., 2013; International Union of Railways, 2016).

For the last phase of the supply chain under observation, we will take into account the emissions deriving from the handling of a single container by road from the railway terminal of the Duisburg Freight Village to the container terminal of the port of Hamburg, for a total distance of 371.4 kilometers, covered in 5 hours and 42 minutes, considering a standard TEU weighing 20 tons handled by a truck capable of carrying up to 25 tons, where the average consumption is estimated to be 221.46 grams of diesel per kilometer (Keller et al., 2019). Then with a simple arithmetic calculation we can quantify the fuel consumption equally to 82.3 kilograms and consequently the direct emissions of 322.1 kg of CO2 equivalent following the Table C in the appendix. The indirect emissions will consider that each kilogram of diesel fuel

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[5] Route is based on the analysis of the Evergreen-line vessels, using different sites for the elaboration of the route: https://ss.shipmentlink.com, www.evergreen-line.com and https://www.vesselfinder.com.

will produce 818.4 grams (Prussi et al., 2020) of equivalent carbon dioxide: it is thus possible to define the indirect emissions to 67.3 kg of CO_2 equivalent. Finally, by adopting the adjustment factors, the direct emissions will be 338.2 kg CO_2 equivalent while the indirect emissions will be 68.7 kg CO_2 equivalent.

Therefore, it is possible to quantify the carbon footprint generated by the entire logistics chain for the movement of a single container from Port Said to the logistic hub of Hamburg, evaluated as the sum of the different transport modes expressed in a kilogram of CO_2 equivalent.

Table 4 summarizes the different emission profiles for the different modes of transport.

Way of Transport	Direct Emissions	Indirect Emissions	Total Emissions
Marine Vessel	313.1 kg CO_2eq	21.9 kg CO_2eq	335 kg CO_2eq
Rail Transport	-	-	659.6 kg CO_2eq
Road Transport	338.2 kg CO_2eq	68.7 kg CO_2eq	406.9 kg CO_2
Total Emissions	651.3 kg CO_2eq	90.6 kg CO_2eq	1,401.5 kg CO_2eq

Table 4. Total Emission for a logistic value chain from Port Said to Hamburg – Emission in kg of CO_2 equivalent per TEU. Source: author's elaboration based on previous emissions quantification.

We can therefore assert that the Carbon Footprint for a single TEU from Port Said to the logistics hub in Hamburg is 1,401.5 kilograms of CO_2 equivalent.

4. Conclusions

Starting from an assessment of the average emission sources for each category of vehicle used in modal transport, a calculation model has been developed that can provide useful information in terms of absolute volumes of emissions and their intensity for each unit moved, following a standardized and uniform approach to quantification, (McKinnon, 2010) and attempting to reduce some of the discretion arising from the assessment of emissions (McKinnon et al., 2015).

It should be emphasized that there is a problem of discretion in the quantification of carbon footprint. It is relevant to outline the boundaries within which to develop the analysis of emissions. This has been the reason leading to the application of an adjustment factor that would include all the omitted and exogenous emissions factors. Thus, the proposed adjustment factor becomes crucial to concretely defining the boundaries of the calculation model for assessing emissions from a supply chain and pursuing the criteria of comparability and transparency set for the drafting of the Carbon Footprint, as it limits all discretion (IMO, 2018). However, the importance of the carbon footprint must not be limited to the mere numerical value expressed in the quantity of equivalent carbon dioxide produced in a specific production process. The strength of the indicator of the carbon footprint is given by the combination of the quantitative aspect and its communication (Schmied and Freid, 2012). Generally, the quantitative aspect is most relevant, but the concept of communicability assumes central importance within the concept of Carbon Footprint: it is a clear and direct tool to highlight a specific component of the life cycle of a process, which can univocally represent useful information in terms of environmental sustainability, (McKinnon, 2010) but above all, a performance indicator, thus representing a comparative advantage in terms of environmental issues (IMarEST and IMO, 2018; Franchetti and Apul, 2013).

From the case study discussed, it is possible to highlight how economies of scale have a significant impact in the field of emissions generated in freight transport. On an absolute level, the naval segment is undoubtedly the preponderant one in terms of emissions. Nonetheless, we can observe how per single TEU this becomes the most efficient mode of transport. From this perspective, the naval gigantism we are now witnessing will also involve a reduction of emissions per single unit of freight transported.

The calculation model presented for the indicator of Logistics Carbon Footprint represents the first instance to be addressed regarding the abatement of emissions from the transportation sector, an extremely complex challenge but, at the same time, a crucial first result regarding environmental sustainability.

Appendix:

	Class by size	Unit of Measure	Avg. engine power (in kWh)	Average speed (Knots)
Bulk Carrier	0-9,999	DWT	1,687	9.9
	10,000-34,999		7,112	11.6
	35,000-59,999		9,548	12.2
	60,000-99,999		10,989	12.3
	100,000-199,999		18,997	12.7
	200,000 - +		22,740	12.8
Container	0-999	Teus	6,182	12.7
	1,000-1,999		13,152	14.5
	2,000-2,999		22,640	16.2
	3,000-4,999		39,328	17.2
	5,000-7,999		52,556	17.5
	8,000-11,999		57,901	17.9
	12,000-14,500		61,231	17
	14,500 – 19,999		60,202	16.4
	20,000 - +		60,241	16.3
General cargo	0-4,999	DWT	1,107	8.8
	5,000-9,999		3,471	10.4
	10,000 -+		7,910	12.2
Oil tankers	0-4,999	DWT	1,414	8.9
	5,000-9,999		3,134	9.3
	10,000-19,999		5,169	9.8
	20,000-59,999		8,570	11.9
	60,000-79,999		12,091	12.4
	80,000-119,999		13,518	11.9
	120,000-199,999		17,849	12.5
	200,000 - +		26,710	12.9
Ro-Ro	0-4,999	DWT	1,751	9.2
	5,000 - +		11,526	14.4

Table A. Ship category and main engine power. Source: author’s elaboration on “fourth study of GHG” of IMO 2020 pp. 99-101.

			Average consumption (tons per day)	
	Class by size	Unit of Measure	Main Engine	Auxiliary Engine
Bulk Carrier	0-9,999	DWT	6.0	1.8
	10,000-34,999		16.2	1.7
	35,000-59,999		20.6	2.2
	60,000-99,999		23.7	3.4
	100,000-199,999		37.9	2.9
	200,000 - +		51.6	2.8
Container	0-999	Teus	13.3	3.6
	1,000-1,999		24.3	7.1
	2,000-2,999		35.9	6.8
	3,000-4,999		51.6	9.8
	5,000-7,999		78.7	9.3
	8,000-11,999		101.1	11.1
	12,000-14,500		110.6	13.4
	14,500-19,999		105.6	14.8
	20,000 - +		100.0	17.1
General cargo	0-4,999	DWT	3.5	0.6
	5,000-9,999		8.0	2.3
	10,000 -+		14.6	3.6
Oil tankers	0-4,999	DWT	3.7	3.0
	5,000-9,999		6.3	4.2
	10,000-19,999		10.3	6.6
	20,000-59,999		20.5	6.0
	60,000-79,999		26.8	5.2
	80,000-119,999		27.7	6.2
	120,000-199,999		36.4	8.2
	200,000 - +		57.5	6.7
Ro-Ro	0-4,999	DWT	5.4	7.0
	5,000 - +		30.3	7.0

Table B. Ship consumption per category.
Source: author’s elaboration on “fourth study of GHG” of IMO 2020 pp. 99-101.

Category	Average Speed	Average Consumption			Emission Factors			
				CO_2	CH_4	N_20	NO_x	PM
Dimension in tons	km/h	g/km	km/l	g/km				
< 7.5	64.74	127.02	6.56	408.67	0.01	0.35	2.15	0.13
7.5-14	64.73	154.14	5.41	494.11	0.01	0.41	3.02	0.13
14-20	64.65	185.66	4.49	559.09	0.01	0.53	3.44	0.13
20-28	64.72	221.46	3.76	691.09	0.01	0.59	3.71	0.13
28-34	64.67	257.56	3.24	795.79	0.01	0.68	4.03	0.13
34-40	64.64	271.32	3.07	808.94	0.01	0.77	4.51	0.14
40-50	64.58	302.93	2.75	953.65	0.01	0.91	5.27	0.14
50-60	64.64	378.01	2.20	1,183.24	0.01	1.29	6.58	0.14

Table C. Average consumption and emissions per heavy duty trucks.
Source: author's elaboration on "Handbook emission factor for road transport" (HBEFA), 2019: Microsoft Access Database[6].

Type of Train	Gross Tons Weight Train	Energetic Consumption (kWh/t-km)	Energetic Consumption (kWh/km)	Emission CO_2 (gCO_2/t-km)	Emission CO_2 (kg CO_2/km)
Light	500 t	1.1	701.8	22.8	14.5
Average	1,000 t		1,252		25.9
Large	1,500 t		1,802		37.3
Extra-large	2,000 t		2,352		48.7
Heavy	5,000 t		5,652		117.1

Table D. Emission for freight trains.
Source: author's elaboration on García-Álvarez et al., 2013, p. 3; EcoTransIt World Initiative, 2019, pp. 58-62.

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[6] "The Handbook of Emission Factors for Road Transport (HBEFA) was originally developed on behalf of the Environmental Protection Agencies of Germany, Switzerland, and Austria. Today, other countries (Sweden, Norway, France) as well as the JRC (European Research Center of the European Commission) support HBEFA. HBEFA provides emission factors, i.e., the specific emission in g/km for all current vehicle categories (PC, LDV, HDV, buses and motorcycles), each divided into different categories, for a wide variety of traffic situations. Emission factors for all regulated and the most important non-regulated pollutants as well as fuel/energy consumption and CO2 are included". Citation from HBEFA website: https://www.hbefa.net/e/index.html.

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