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Framework for assessing the environmental impacts of intermodal transportation

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ABSTRACT
This research aimed to use a sustainable approach based on the internalisation of external cost analysis of intermodal transportation of freight to assess the impacts of these activities on the environment. This research used two approaches to develop a model that illustrates the internalisation of the external cost of freight transport. The first approach was used to calculate the cost of emissions for each route considering the transportation and its' cost in the country of destination. The second approach calculated the external cost considering only the distance travelled by the vehicle. The results showed that the companies operating in the selected scenarios would have to pay an additional cost for the transportation of goods. The scenarios had different pollutants emitted during the transportation, which means that the negative impact on human health and the environment is evident. The urgency to limit carbon dioxide and other greenhouse gases in the atmosphere has increased concerns for all activity sectors. Climate change has drawn the attention of governments, companies, and academics, promoting initiatives that mitigate the impact of their activities. The model for measuring emissions was used due to the need for a comprehensive cost analysis to further assess the impact on the environment. Regarding the internalisation of the external cost emissions, the findings showed that different scenarios had a different pollutant emitted during the transportation, which means that the negative impact for human health and the environment is evident. Findings also indicate that to minimise the impact during the transportation, considering the "user-pays principle", these impacts should be discussed in more detail between stakeholders.

KEY WORDS
sustainability, intermodal transport, CO2 emissions, internalisation of external cost

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Introduction

The urgency to limit carbon dioxide and other greenhouse gases in the atmosphere has increased in all sectors. Climate change has drawn the attention of governments, companies, and academics, promoting initiatives that mitigate the impact on the climate. The concern focused on activities with a more significant rate of carbon dioxide and other greenhouse gas emissions, such as freight transport (Rossi et al., 2021). Nevertheless, for this sector, several initiatives have been considered for greening transportation,

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with intermodal transport as the main strategy for a sustainable alternative (Tamannaei et al., 2021).

Over the last few years, the possibility of industries to operate in a global market has been contributing to an increase in the transportation of goods by highways. Transportation is considered a key sector for several countries and one of the main sources of CO2 emissions (Wang et al., 2020). This economic activity leads to external costs arising from the pollutant that drives climate change and impacts society (Musso & Rothengatter, 2013).

The growth of freight transport in the global market has increased concerns regarding the negative impact on air quality and climate change. Transport is mainly driven by the combustion of fossil fuels, which results in the emission of various greenhouse gases such as carbon dioxide (CO2), nitrogen (NOx), and sulfuric oxides (SOx) (Aldakhil et al., 2018).

The current literature focuses on studies highlighting the importance of internalisation of external transport costs in companies (Tamannaei et al., 2021). The external costs of freight transport can be divided into two categories: (1) those related to internal costs, which involve traffic, accident costs, and urban road problems, and (2) those external to the sector, such as environmental problems, noise, and health problem imposed upon society.

Considering the importance of intermodality in transport as a strategy to minimise CO2 emissions and the need to assess the internalisation of the external cost of freight transportation, this research had a dual aim: first, it aimed to analyse the contribution application of intermodality to reduce the emission generated by a furniture company, and second, it assessed internalisation of the external costs of emissions in the freight transport using a furniture company as a case study.

1. Theoretical background

According to data estimated by the International Energy Agency (International Energy Agency, 2021), CO2 emissions in the transport sector represented about 24 % of all greenhouse gas emissions in 2020, and it is expected to continue growing in the coming years. In the case of urban carbon emission, this sector is also one of the primary sources, especially the activities related to passenger transportation.

The growing global demand for the transport of goods has been increasing significantly, raising concerns regarding the impact of these activities on the environment (Mhana et al., 2023). According to Kwakwa et al. (2022), the impact caused by this sector on climate change has prompted companies and governments to develop policies aiming to minimise temperature limits. Despite some initiatives, such as the use of electric vehicles instead of internal combustion engines, most goods are transported using vehicles powered by combustion engines.

The transport sector is constantly changing due to technological advances that have been contributing to more efficient solutions for freight transport in terms of time and costs (Kinsella et al., 2023). Intermodality has been gaining importance and popularity as a system for transporting goods over long distances by different transport types via ports, coastal routes, waterways, railways, roads, and airways (Bartholomeu et al., 2020).

According to Zhang et al. (2023), over the last decades, the fast-growing international market trade has been contributing to the change in the mindset of globally operating companies regarding the traditional way to transport goods, which has led to such strategies as intermodality to minimise emissions. This is especially true in the case of international freight. The authors claimed that intermodality is a key element contributing to the promotion of green transport and emission reduction. It can also shed light on implications to the efficiency of these activities for the countries that have been emerging in the intermodal competition.

Traditional models of logistics management are focused on minimising transport costs, but due to the increase in CO2 emissions in the last decades, it is imperative that new models and technologies are developed to help companies minimise and control it (Qu et al., 2016). Also, the urgency to green transport has led players from the logistics sector to increase concerns about the negative impacts of these activities on the environment and society. Impacts such as emissions, noise, and vibration, which can cause health and safety risks to human life, need to be better analysed and discussed (Petro & Konečný, 2017).

However, the current literature related to green transportation and decarbonisation of this sector does offer an intermodality strategy to minimise the impact of these activities on the environment. The situation was the main motivation for this research, i.e., bringing to light the link in the discussion between three main aspects: intermodality, environmental costs, and internalisation of these costs.

2. Research methods

This research focuses on two main data sources: the DHL Carbon Calculation, which is a platform widely used by companies and researchers to quantify CO2 emissions in transportation, considering different scenarios and transport modes, and data from a furniture company.

Fig. 1 summarises the main steps that served as instruments for considering the development of this research.

The calculation of CO2 emissions used in the DHL's Carbon Calculator can be found online and free of charge on the DHL platform (DHL, 2021). The methodology used in the platform is in line with the reports published by IPCC (Bednar-Friedl et al., 2015), which focus on the role of transportation in mitigating climate change. This work was also inspired by Lagoudis and Shakri (2015), who developed a framework to measure carbon emissions for inbound transportation, considering cargo distribution between air and sea as variables. For the creation of the scenarios, some aspects were considered, i.e., the cost of transport and the time required for transport. Then, these values were used to estimate CO2 emissions using data provided by a forwarding company. In this research, the CO2 values in the "SCENARIOS" represent the CO2 emissions from the combustion of fossil fuels used to transport the configured shipment scenario. The emission calculations are based on the guidelines outlined in the Greenhouse Gas Protocol, the Corporate Accounting and Reporting Standard, and the Corporate Value Chain Accounting and Reporting Standard.

The data was also prepared in accordance with the requirements of the European Emissions Trading System and the standards EN 16258 (European Commission, 2021) and ISO 14064 (ISO, 2021). The Carbon Calculator was used to create the scenarios, considering the waypoints between a pair of origin and destination locations based on a network dataset specific to the mode of transport and linking the waypoints to build a route. The sum of all connected waypoints shows the shortest distance travelled on that route. If an inserted location is not part of the mode-specific network data set, using a built-in algorithm, the Carbon Calculator adds a connection from that location to the nearest location that is part of the mode-specific network data of joint transport.

A set of scenarios was created to obtain a picture of CO2 emissions generated by the transport of products by a company. This research considered three routes: Matosinhos (PT) – Valls (ES), Penamaior (PT) – Erfurt (DE), and Tábua (PT) – Piacenza (IT). The DHL Carbon Calculator helped to determine the

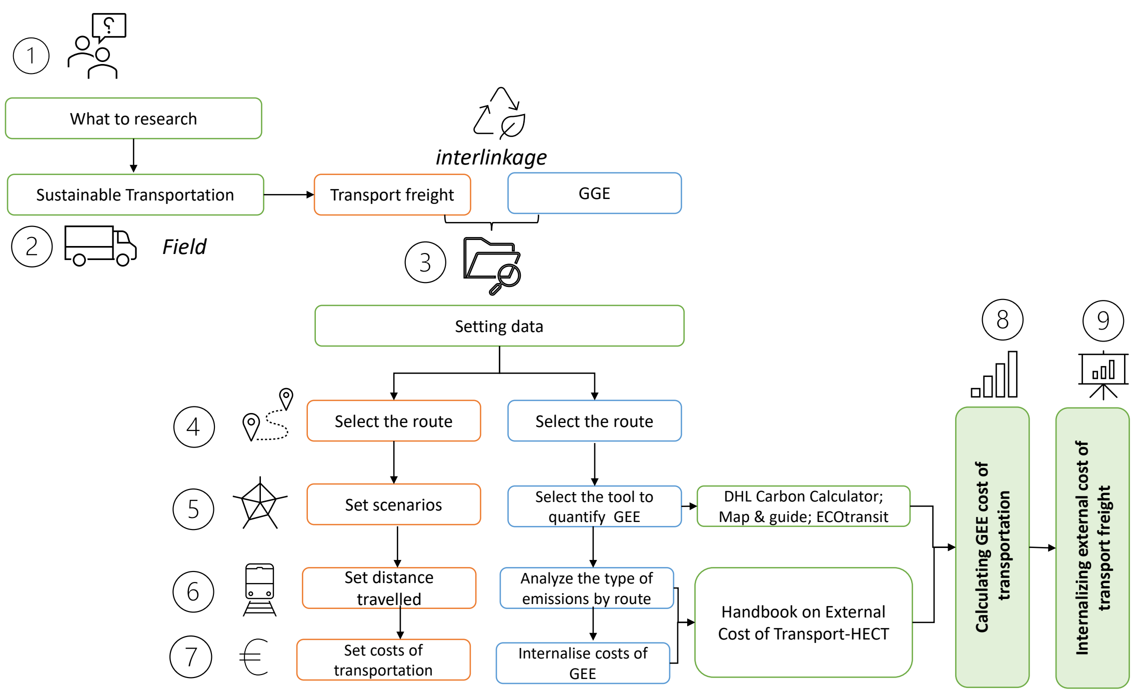

Fig. 1. Main steps used in considering the research

ideal scenario for each route, i.e., Matosinhos (PT) – Valls (ES): using the road–rail–road intermodality; Penamaior (PT) – Erfurt (DE): using the road–maritime–road intermodality; and Tábua (PT) – Piacenza (IT): using the road–maritime–road intermodality. All of them were analysed considering the relationship between the reduction in CO2 emissions, costs and time of transportation, and distance.

3. Case of a furniture company

The environment can affect the business of organisations in several ways, including the scarcity of resources, the socio-demographic context, and the presence of competitors. As a consequence, over the last decades, companies have been pushed to develop projects in the planning and construction of strategies to minimise the cost of its impacts on the environment. Transport has been seen as a longwinded part of these strategies, especially when defining routes to transport companies' goods (Schirone & Torkan, 2012).

In this research, a furniture company was used as a case study to illustrate the impact of transportation on climate footprint. Since transport intermodality can be considered a driver towards reducing CO2 emissions and offering solutions that result in low CO2 content and low costs, this research focused on suggesting a set of alternatives for transportation of the company's products in a more sustainable way.

In the last report published by the studied furniture company in 2020, relative to the previous year, the company indicated that its biggest long-term goal was to reduce its climate footprint by the year 2030 when compared to 2017, in which the footprint value was 1.2 million tons of CO2. The company is greatly concerned with sustainability and environmental impacts. For this research, a combination of different transport modes was considered, with the aim to propose the one with the lowest CO2 emissions. As presented in Table 1, for the calculation of CO2 emissions, three routes were identified from where transport will be dispatched to the destination.

The locations for the departure, transport, and reception of goods were chosen in cities where the company has stores and distribution centres. For the development and calculation of scenarios, it is necessary to consider some assumptions directly related to the adopted cost values, and these values were identified by a freight forwarder with extensive experience in the market:

- Regarding road transport, the travel cost was calculated based on kilometres travelled.
- Routes with less than or with 100 Km were estimated at a cost of EUR 100. In these cases, it was impossible to count the travel cost for the route as it is not compensatory for freight forwarders since there are fuel costs, maintenance costs, and delays in loading and unloading, which can lead to the inability to provide the next service. Thus, it is necessary to estimate a value that can cover all possible costs. For journeys over 100 km, the estimated cost will be EUR 1 per kilometre.
- For the sea route, the values were estimated according to the destination. The cost of sea freight to Spain was EUR 950. For Germany, sea freight was EUR 1250, and for Italy, the cost was EUR 1150. To the value of the sea freight, whatever the destination, the tax should be added, which is always charged for the pollution emitted by maritime transport. In this case, the value used as an estimate was EUR 25, but it is updated every month.
- For the railway mode, it was necessary to consider the cost of rail freight, which also varies according to the destination and the handling cost, which is the cost that the terminal had in handling the loads, and a fixed value of EUR 20 per movement was estimated. The cost of rail freight to Spain was approximately EUR 400, to Italy EUR 500 and to Germany EUR 600.

Table 2 details the configuration for each combined scenario, considering the starting point to the destination point. A set of scenarios was suggested for each route (Table 2), aiming to understand the difference between transport modes. Three cities in Portugal and three different countries (Germany, Spain, and Italy) were taken as a sample. These countries were chosen because the company has large distribution centres in them.

Additionally, to assess the external cost of these activities, an analysis was developed, focusing on scenario S1, which was the only one using road transport. This analysis was developed considering different steps: (1) emission calculation for the type of pollutant in each route, (2) analysis of individual costs for the type of pollutant generated during the transport for each country, (3) analysis of emission costs by category of vehicle, and (4) calculation of

Tab. 1. Proposed case study scenarios

Route	Origin	Destination
R1	Matosinhos, PT	Valls, ES
R2	Penamaior, PT	Erfurt, DE
R3	Tábua, PT	Piacenza, IT

Tab. 2. Details of chosen routes

	Routes		
Scenarios	Matosinhos (PT) – Valls (S)	Penamaior (PT) – Erfurt (DE)	Tábua (PT) – Piacenza (IT)
S1	Road	Road	Road
S2	Road – Rail – Road	Road – Sea – Road	Road – Sea – Road
S3	Road – Sea – Road	Road – Rail – Road	Road – Rail – Road
S4	Road – Sea – Rail – Road	Road – Sea –Rail – Road	Road – Sea – Rail – Road

emissions for route considering two methods (M1: individual cost for type of pollutant per route and M2: total cost of emissions by distance travelled).

For the calculation of the external cost of freight transport, the main source of data was the DHL Carbon calculator ECOTransit (ECOtransit, 2022), which is a tool widely used to identify the negative environmental impacts related to freight transportation and the Handbook on External Cost of Transport-HECT version 2019 (European Commission, 2019).

4. Research results

The results presented in this section summarise the novelty of this research, which has two main aspects: highlighting the need for further discussion among companies on understanding the environmental impact of transportation and the contribution of intermodality as a logistics strategy to the reduction of CO2 emissions.

The first analysis was made after defining the configuration of each route. It is important to highlight that for all scenarios, a total of 20 tons of products was considered. Since this research focused on quantifying emissions for different routes, the next sections will discuss the results achieved in each case. The costs presented in the following tables are related to the costs defined by the selected company for the value paid by the freight.

4.1. Characterisation of the proposed routes versus scenarios

4.1.1. Matosinhos (PT) — Valls (S)

For the case of the Matosinhos (Portugal, PT) — Valls (Spain, S) route, the results in Table 3 show that Scenario 1 was the most effective in terms of the number of kilometres and in terms of transport time; on the other hand, Scenario 2 is the most effective with the level of costs and CO2 emissions.

For Scenarios 3 and 4, the results showed that they were considered unsuccessful on the variables chosen for the study because the distance, costs and emissions have a higher value. Scenario 3 combines transportation by road and sea; this modality significantly contributes to the increase of each variable's value. The value increased because a sea route was used. The freight from Leixões Port in Portugal to Barcelona costs almost EUR 1000, and it takes about 48 hours, with a distance travel of approximately 2325.84 Km. In terms of CO2 emission, the results showed that the route emits about 550.69 KgCO2.

Compared to Scenario 1, PT-S_S3 would be more effective in terms of costs and CO2 emissions but not in terms of time and distance, as it takes more time and travels more kilometres. Thus, PT-S_S2 was con-

Tab. 3. Results for Matosinhos (PT) — Valls (S)

	Distance (Km)	Cost (EUR)	Time (hour)	CO2 Emissions (KgCO2)
S1	1063	1063	13	944.05
S2	1247.44	659.16	20	502.23
S3	2434.52	1163.19	50	647.19
S4	2549.33	1849.47	72	1408.13

sidered the most effective intermodality proposal for the Matosinhos (PT) — Valls (ES) route since the one that contains lower costs and a low CO2 emission level.

4.1.2. Penamaior (PT) — Erfurt (DE)

Four scenarios were analysed for the Penamaior (PT) — Erfurt (DE) route. In this case, the results showed that route PT-DE_S1 was considered the most effective in terms of the number of kilometres and time. PT-DE_S1 was positive in terms of cost-effectiveness. Finally, for the case of PT-DE_S4, the results demonstrate the scenario's effectiveness in terms of CO2 emissions. Despite not being effective in any of the variables, PT-DE_S4 presents very attractive CO2 emissions compared to Scenarios 3 and 1. In this scenario, three modes of transport were considered, namely road, sea, and rail.

The scenario with the longest route is maritime and leads to low CO2 emissions compared to, e.g., the road mode. In terms of costs, it is no longer as attractive because the combination of sea and rail modes was considered, and even the road mode showed a higher value than the other scenarios that only combine two modes of transport. Regarding the number of kilometres, PT-DE_S4 has more than other scenarios since it is necessary to create a route that can include the three modes. For the time needed for the transport, it is normal that it will be necessary for around seven days because in PT-DE_S2, the modes are slower and where there is a possibility of more delays or accidents. So, the results showed that PT-DE_S2 was considered the most successful scenario for the Penamaior (PT) — Erfurt (DE) route.

4.1.3. Tábua (PT) — Piacenza (IT)

For this route, Tábua (PT) — Piacenza (IT), the platform results showed positive evaluations for PT-IT_S1 for time and number of kilometres. PT-IT_S3 is the most cost-effective scenario, and PT-IT_S2 would be the best choice for CO2 emissions.

The PT-IT_S4 scenario is ineffective for all variables and results in Table 5 show that it takes the longest from the beginning to the destination. Regarding CO2 emissions, PT-IT_S4 ranks second behind Scenario 3, with a slight difference of 81.42 KgCO2. For this scenario, the marine mode was combined with the railway in the part of the route with more kilometres to achieve less emissions since more kilometres mean more emissions.

Finally, this was the scenario with the highest cost, as freight to Italy by sea is expensive, and the remaining costs are also high. For this route, the

Tab. 4. Results for Scenario Penamaior (PT) — Erfurt (DE)

	Distance (Km)	Cost (EUR)	Time (hour)	CO2 Emissions ($KgCO_2$)
S1	2394	2394	25	2125.65
S2	2744.30	1940.52	58	1184.53
S3	2770.14	1415.78	85	1685.15
S4	2826.01	2571.71	129	1311.35

Tab. 5. Results for Tábua (PT) — Piacenza (IT)

	Distance (Km)	Cost (EUR)	Time (unit)	CO_2 Emissions ($KgCO_2$)
S1	1915	1915	22	1700.35
S2	3187.69	1646.91	79	1006.89
S3	2201.12	801.53	54	1194.55
S4	3456.07	1964.27	77	1113.13

results showed that the intermodality scenario PT-IT_S2 emits the lowest CO2 content.

4.2. Model for internalisation of external costs of transportation: an unimodal illustration

As a vital sector worldwide, the transport sector plays an important role in the supply chain; however, as discussed before, the environmental impact generated by transportation is not the only impact of this activity, and the effects on human health are also a great concern. To illustrate both impacts, this research aimed to assess the impact of activities of each scenario presented in Table 1. To improve this analysis, a model was developed based on "user pays" and "polluter pays" principles (Auditors, 2021), as this approach maintains that polluters should bear the pollution costs, including the cost to measure, prevent, and remedy problems imposed on society.

The analysis concerned each scenario for the impact of transport on the environment and society. The emission of toxic and other substances that can impact global warming and human health was considered. Table 6 presents the main substances considered in this research.

The substances presented in Table 6 were considered in the analysis of the amount of each element emitted to the air through the combustion engines of each route proposed. It is important to highlight that for the internalisation of external costs, a set of aspects were considered: (1) emissions produced by tons for each scenario, (2) the cost for individual emissions by country for each scenario (costs were estimated based on the methodology developed by European Commission, version 2019 (European Commission, 2019)), and (3) costs for emissions by category of the vehicle used in the transportation (European Commission, 2019).

The internalisation of external costs aims to input costs to entities that are responsible for any negative or positive effects of their activities on society (Petro & Konečný, 2017). In this research, carbon calculators were used to calculate the emissions for the assessment of internalisation of external costs; instead of using the DHL carbon calculator, the ECOTransit calculator was used (ECOtransit, 2022). The ECOTransit is a tool widely used by academics and companies to identify the negative environmental impacts related to freight transportation. The tool was selected for use in this research due to the possibility of accessing data related to N2O, NOx, and PM, which is a limitation of the DHL carbon calculator.

Table 7 summarises the ECOTransit results after entering data from each route proposed in this study. The results presented in the table only considered routes that used roads to transport; for this analysis, only S1 was considered (Table 2).

To standardise the results, the outputs presented in Table 7 were considered in the calculation of the approaches Well-to-Wheel (WtW) and Tank-to-Wheel (TtW). The first (WtW) considers the energy consumption and emissions generated from the energy production for its final consumption. The

Tab. 6. Overview of transport freight emissions and their impact

Substances	Main negative impacts	Acronymous
Nitrogen oxides	Contributes to summer smog, acidification, and damages human health	N2O
Non-methane hydrocarbon	Contributes to summer smog and damages human health	NOx
Sulphur dioxide	Contributes to acidification and damages human health	SO2
Particulate matter	Damages human health	PM

Source: European Commission, 2019.

Tab. 7. Summary emissions for an overview of emissions caused in the transport freight in tones

Matosinhos (PT) — Valls (S)						
S1	**CO2**	**CO2 e**	**NOx**	**SO2**	**N2O**	**PM**
tones	75	78	23.99	27.36	206	4.2
Penamaior (PT) — Erfurt (DE)						
S1	**CO2**	**CO2 e**	**NOx**	**SO2**	**N2O**	**PM**
tones	167	174	53.12	61.33	463	9.44
Tábua (PT) — Piacenza (IT)						
S1	**CO2**	**CO2 e**	**NOx**	**SO2**	**N2O**	**PM**
tones	135	141	43.18	48.81	376	7.68

Tab. 8. Summary of the marginal costs for transport by category of vehicle (eurocent per km)

Vehicle category - articulated			Metropolitan area		Urban area			Rural area	
	Full type	EURO — Emission class	Motor-way	Urban road	Other road	Motor-way	Urban road	Motor-way	Urban road
	Diesel	Euro 0	2.18	3.92	2.41	1.59	2.81	0.94	1.05
		Euro I	1.59	2.98	1.77	1.15	2.07	0.68	0.76
		Euro II	1.47	2.39	1.53	1.15	1.96	0.68	0.74
		Euro III	1.11	2.07	1.24	0.9	1.64	0.54	0.6
		Euro IV	0.65	1.1	0.72	0.6	1.01	0.36	0.4
		Euro V	0.32	1.2	0.45	0.26	1.08	0.16	0.223
		Euro VI	0.03	0.12	0.04	0.03	0.11	0.02	0.03

Source European Commission, 2019.

Tab. 9. Summary of the marginal costs for rail transport

Rail Freight transport	Full type	Train type	Traction	Eurocent/pkm or eurocent/tkm	Eurocent/train-km
	Diesel	Long container	Diesel	0.03	0.42
		Long bulk	Diesel	0.03	0.43
		Short container	Diesel	0.07	0.37
		Short bulk	Diesel	2.07	0.36

Source: European Commission, 2019.

second (TtW) merely reflects the emissions and energy consumption during the vehicle operation.

A truck powered by a diesel engine, loaded with 20000 kg and a full capacity of 24000 kg, was considered for the vehicle characteristics. To calculate the cost of emissions for each type of vehicle, this research considered the methodology developed by the Handbook on External Cost of Transport (HECT) (European Commission, 2019), which is well-known among academics and industries to provide an overview of the main external costs of transports in several countries. Table 8 presents a summary of the marginal costs for road (Km/Tkm) by category of vehicle and area of operation.

According to the methodology developed by HECT, there are two ways to calculate the costs of freight transport emissions. The first method can be calculated by quantifying each pollutant's emission in euros (EUR/tonne). For this case, it was necessary to summarise the cost of each pollutant by country considered in the scenario. Table 11 summarises the price of the individual cost emissions (EUR/Kg) for countries considered in this research. The data are related to the latest version of the methodology (HECT).

The second method is calculated considering the distance travelled by the vehicle (Tables 3, 4 and 5). In this case, the marginal cost was considered, and the vehicle type is classified as a EURO V, for motorway, used in a metropolitan area, and powered by diesel (Table 8).

In this research, to illustrate the internalisation of the external cost of freight transport from Portugal, both methods were used based on data presented in Tables 8, 9, and 10. The results for the first method, namely the cost for individual emissions for each route, are presented in Table 12. They were calculated considering the emissions caused during transportation and their cost in the country of destination (for all routes, Portugal was chosen as the country of origin).

The results presented in Table 10 summarise the total costs of emissions in euros for each scenario. The calculation showed that for Scenarios PT-S_S1 and PT-DE_S1, the costs of CO2 emissions are higher than NOX, SO2, and PM2.2. Only for Scenario PT-IT_S1 are the costs of NOX higher than CO2. Also, when comparing the costs of freight to the final cost of emissions by each route, it is evident that the costs of emissions are higher for PT-DE_S1 (12 %) and PT-IT_S1 (76 %). Once this research attempts to analyse the external costs of transportation in the light of the "polluter pays" principle, the results show that for the selected scenarios, companies operating in those scenarios would have to pay an additional amount of 12 % and 76 % for the transportation, and

Tab. 10. Summary of the marginal costs for maritime transport

	Vessel type			
Tank-to-Wheel emissions maritime transport	Small container vessel (28,500 gt)	Distance at sea (km)	Eurocent per pkm or tkm	EUR per vessel-km
		500	2.09	11
		3000	0.13	31
	Large bulk vessel (143,000 gt)			
		500	0.04	47
		3000	0.03	37
		15000	0.03	35
	Small bulk vessel (18,000 gt)			
		500	0.06	9
		3000	0.03	6
	Large bulk vessel (105,000 gt)			
		500	0.02	22
		3000	0.01	15
		15000	0.01	14

Source: European Commission, 2019.

Tab. 11. Summary of the individual cost of emissions by country (EUR)

	NH3	NMVOC	SO2	NOx city	Nox rural	PM2.5 metropole	PM2.5 city	PM2.5 rural	CO_2
PORTUGAL	4.3	0.5	4.1	2.8	1.7	292	94	39	12.3
SPAIN	6.4	0.7	6.8	8.5	5.1	348	112	46	11.9
GERMANY	28.1	1.8	16.5	36.8	21.6	448	144	93	39.6
ITALY	2.6	1.1	12.7	25.4	15.1	409	132	79	17.2

Source: European Commission, 2019.

Tab. 12. Method 1, a summary of the cost of freight vs costs of emissions by route (EUR)

M1	CO_2	N0x	SO2	PM2.5	Cost of freight	Total cost of emissions
R1	360.7	67.1	112.1	394.8	1063	934.8
R2	803.2	451.5	417	1057.2	2394	2729.1
R3	649.3	1096.7	619.8	1013.76	1915	3379.7

Tab. 13. Method 2, a summary of the distance travelled vs costs of emissions by scenario

M2	Distance (Km)	Cost of emissions by scenario (EUR)
PT-S_S1	1063	340.16
PT-DE _S1	2394	766.08
PT-IT_S1	1915	612.8

only Scenario PT-S_S1 presents the costs lower than the price of freight (-12 %). It is important to highlight that these costs should be paid due to the damage that may be done to society and the environment during transportation.

In this research, a second method was also considered in the assessment of the costs of emissions from road transportation, and the results are presented in Table 13.

The second method is simpler than the first as it only considers the distance travelled (in this case, only highways were considered), and the vehicle category (EURO V) resorts to the cost of the emission class of the vehicle (Table 8). It is considered a limitation since the cost of the type of pollution is not available, which is very important to consider because of the environment and people's health. Yet, when comparing both methods, the results showed that the costs are significantly lower, which means that this method has weaknesses and does not contribute to assessing the external costs of freight transport.

5. Discussion

5.1. Internalisation of external costs considering intermodal transportation

This section applies an analysis of the internalisation of the external costs considering the intermodal transportation in an international route between Matosinhos in Portugal and Valls in Spain (Route 1). The analysis presented in this section will focus on four different intermodal scenarios.

Scenario 1. Road

The results presented in Table 14 summarise the main pollutant for the route Matosinhos — Valls when considering road transportation. It is important to highlight that the results differ from those presented in Table 7 due to the need to standardise the unit of measure, which means that for the intermodal analysis, all the presented results considered the emissions of CO2 in tons, and for NOx, SO2, and N2O in kilograms.

Regarding the costs associated with Scenario 1, Tables 15 and 16 summarise the results for the costs of emissions when transporting goods by road transport. For this scenario, both methods show that the costs of emissions are higher than the costs of freights paid by the company. It is more significant for Method 2 since the method considered different types of pollutants.

Scenario 2. Road–Rail–Road

Based on the methodology proposed in this research, Table 17 summarises the results for each type of pollutant emitted during transportation when considering three stages: (1) the load departs from Matosinhos (PT) to Alfarelos (PT) by truck, (2) then goes to Alfarelos to Constanti (S) by rail, and finally, (3) from Constanti to Valls (S) by road. This scenario was considered due to the capability to connect road and rail transportation. According to Merchan et al. (2016), rail freight transportation has a better performance when compared with road transportation. The authors maintained that intermodal rail–road solutions can contribute to minimising the environmental impacts of several pollutants in different categories.

The research results presented in Table 17 showed that despite of the distance travelled, in this scenario, Stage 2 is has the lower emission level when compared with the distance travelled by road.

Tab. 14. Total emissions for Scenario 1

Results for Scenario Matosinhos (PT) - Valls (S)_S1										
Road	Matosinhos→Valls S1	Distance (Km)	Cost (EUR)	Time (hour)	GHG CO_{2E} (WTW)	$C0_2$ (WTW) (tons)	N0x (Kg)	SO2 (kg)	N2O (kg)	PM (kg)
		1065	1063	13	1.57	1.52	0.48	0.55	4.25	***0.085***

Tab. 15. Summary of the cost of freight vs costs of emissions S1

Method 1						
	CO_2 (EUR)	N0x (EUR)	SO2 (EUR)	PM2.5 (EUR)	Cost of freight (EUR)	Total cost of emissions (EUR)
Matosinhos→Valls	7.5517	1.344	2.255	7.99	**1063**	**19.1407**

Tab. 16. Summary of the distance travelled vs. costs of emissions by scenario S1

Method 2				
Matosinhos→Valls	Distance (Km)	Cost of emissions by scenario (EUR)	Total cost of emissions (EUR)	Cost of freight (EUR)
	1065	340.8	**1065**	**1063**

Tab. 17. Total emissions for Scenario 2

Results for Scenario Matosinhos (PT)—Alfarelos (PT)_S2										
Road	Matosinhos→Alfarelos S2	Distance (Km)	Cost (EUR)	Time (hour)	GHG CO2 (WTW)	C02 WTW) (tons)	N0x (Kg)	SO2 (kg)	N2O (kg)	PM (kg)
		139.16	139.16	3	0.2	0.19	0.062	0.072	0.55	***0.011***
Results for Scenario Alfarelos (PT) – Constanti (S)_S2										
Rail	Alfarelos→Constanti S2	Distance (Km)	Cost (EUR)	Time (hour)	GHG CO_{2e} (WTW)	C02 (WTW) (tons)	N0x (Kg)	SO2 (kg)	N2O (kg)	PM (kg)
		1085.45	420	15	0.32	0.31	0.088	0.66	1.51	0.088
Results for Constanti (S) – Valls (S)_S2										
Road	Constanti→Valls S2	Distance (Km)	Cost (EUR)	Time (unit)	GHG CO_{2e} (WTW)	C02 (WTW) (tons)	N0x (Kg)	SO2 (kg)	N2O (kg)	PM (kg)
		22.82	100	0.5	0.0032	0.0032	0.0094	0.012	0.034	0.00096

Tab. 18. Emissions for Scenario S2

Method 1						
	CO_2 (EUR)	N0x (EUR)	SO2 (EUR)	PM2.5 (EUR)	Cost of freight (EUR)	Total cost of emissions (EUR)
Matosinhos→Alfarelos	0.962	0.1736	0.2952	1.034	**139.16**	**2.46**
Alfarelos→Constanti	1.5392	0.03256	4.488	9.856	**420**	**15.91**
Constanti→Valls	0.015392	0.0799	0.0816	0.10752	**100**	**0.10**

Tab. 19. Summary of the distance travelled vs costs of emissions by scenario S2

Method 2				
	Distance (Km)	Cost of emission by scenario (EUR)	Total cost of emissions (EUR)	Cost of freight (EUR)
Matosinhos→Alfarelos	139.16	44.5312	**44.52**	**139.16**
Alfarelos→Constanti	1085.45	401.6165	**401.61**	**420**
Constanti→Valls	22.82	7.3024	**7.304**	**100**

For Scenario 2, the costs were computed considering both methods. For the first method, the results in Table 18 show that the route Alfarelos (PT) to Constanti (S) by rail has higher costs in terms of pollutants. For this route, the individual costs of emissions were calculated considering the costs for Spain (Table 9). This means that, in this scenario, despite the use of intermodality, the costs of emissions also increase when the company uses rail transportation.

The results presented in Table 19 represent the second method. Despite being more straightforward, since the method does not consider different pollutants emitted during the transportation, the results are in accordance with Table 18. Yet, in this analysis, the costs of emissions are significantly higher than the freight for Matosinhos — Alfarelos (Portugal); for the route to Spain the costs are lower.

Scenario 3. Road–Sea–Road

With regard to Scenario 3, the analysis focused on transporting 20 tons of product by three transport modes: (1) Matosinhos (PT) — Leixões (PT) by road, (2) Leixões (PT) — Barcelona (PT) by sea, and last mile Barcelona (PT) — Valls (S) by road. The results for each route and total pollutants emitted are presented in Table 20.

According to Santos et al. (2022), sea shipping is of significant importance in freight transportation worldwide due to the positive economic and environmental benefits of this transport mode. Compared to road transport in terms of cost and time transit, the authors argue that sea transportation has no significant market share in Europe. In this context, the results presented in S3 have considered sea shipping as an important mode to be considered. As presented in Table 20, the results showed that for Scenario 3, most transportation is carried out by sea, meaning that the total amount of emissions is significant.

Regarding the external costs for this scenario, the two proposed transport modes (road and sea) are presented in Tables 21 and 22. The analysis compared the costs of freight that should be paid by the company for each route and the total cost of emissions proposed in this research.

For Method 1 (Table 21), the route Leixões (PT) — Barcelona (S) has a higher cost of freight, but the cost of emissions is lower. It shows the benefit of sea shipping when transporting goods. The costs of emissions are significantly lower when compared with S1 (Table 15), and the distance travelled is very close to the sea route. Method 2 is presented in Table 22. The results are also aligned with the previous method, although for the last route (Barcelona — Valls), the results show that total costs of emissions are higher than proposed using Method 1. However, this method did not consider different types of pollutants.

Scenario 4. Road–Sea–Rail–Road

This section presents the results for Scenario 4 considering all three modes of transport: road, sea, and rail. The main idea of presenting the combination of these modes is to highlight the possibility of combining them using the intermodality approach. The results presented in Table 23 summarise the total emissions for each route, with the sea and rail emitting the most pollutants. The results presented in Table 23 highlight an important aspect that the emissions between rail and road are rather different for

Tab. 20. Total emissions for Scenario 3

Results for Scenario Matosinhos (PT) — Valls (S)_S3										
Road	Matosinhos→Leixões S3	Distance (Km)	Cost (EUR)	Time (hour)	GHG CO_{2e} (WTW)	$C0_2$ emissions (WTW) (tons)	N0x (Kg)	SO2 ((kg)	N2O (kg)	PM (kg)
		11	100	1	0.0051	0.0049	0.0016	0.0018	0.0015	***0.00029***
Results for Scenario Leixões (PT) — Barcelona (S) Results_S3										
Sea	Leixões→Barcelona S3	Distance (Km)	Cost (EUR)	Time (hour)	GHG CO_2 (WTW)	$C0_2$ emissions (WTW) (tons)	N0x (Kg)	SO2 ((kg)	N2O (kg)	PM (kg)
		1850	975	48	0.506	0.5	0.47	6.58	7.71	0.88
Results for Barcelona (S) — Valls (S)_S3										
Road	Barcelona→Valls S3	Distance (Km)	Cost (EUR)	Time (unit)	GHG CO_2 (WTW)	$C0_2$ (WTW) (tons)	N0x (Kg)	SO2 ((kg)	N2O (kg)	PM (kg)
		100.7	100	1.5	0.16	0.16	0.047	0.058	0.18	0.0048

Tab. 21. Emissions for Scenario 3

Method 1						
	CO_2 (EUR)	N0x (EUR)	SO2 (EUR)	PM2.5 (EUR)	Cost of freight (EUR)	Total cost of emissions (EUR)
Matosinhos→Leixões	0.025	0.004	0.007	0.02	**100**	**0.1**
Leixões→Barcelona	2.43	3.99	44.74	98.56	**975**	**149.7**
Barcelona→Valls	0.770	0.400	0.394	0.53	**100**	**2.1**

Tab. 22. Summary of the distance travelled vs costs of emissions by scenario S3

Method 2				
	Distance (Km)	Cost of emissions by scenario (EUR)	Total cost of emissions (EUR)	Cost of freight (EUR)
Matosinhos→Leixões	11	3.52	**3.52**	**100**
Leixões→Barcelona	1850	55.5	**55.5**	**975**
Barcelona→Valls	100.7	32.224	**32.2**	**100**

Tab. 23. Total emissions for Scenario 4

Results for Scenario Matosinhos (PT) — Setubal (PT)_S4										
Road	**Matosinhos - PT→ Setubal - PT S4**	**Distance (Km)**	**Cost (EUR)**	**Time (hour)**	**GHG CO_{2e} (WTW)**	**C02 emis-sions (WTW) (tons)**	**N0x (Kg)**	**SO2 ((kg)**	**N2O (kg)**	**PM (kg)**
		361	354.47	5	0.53	0.5	0.16	0.19	1.42	***0.029***
Results for Scenario Setubal (PT) — Sagunto (S)_S4										
Sea	**Setubal PT → Sagunto - S S4**	**Distance (Km)**	**Cost (EUR)**	**Time (hour)**	**GHG CO_2 (WTW)**	**C02 emis-sions (WTW) (tons)**	**N0x (Kg)**	**SO2 ((kg)**	**N2O (kg)**	**PM (kg)**
		1317	975	48	0.364	0.359	0.34	4.67	5.49	0.62
Results for Scenario Sagunto (S) — Barcelona (S)_S4										
Rail	**Sagunto -S → Barcelona - S S4**	**Distance (Km)**	**Cost (EUR)**	**Time (unit)**	**GHG CO_2 (WTW)**	**C02 emis-sions (WTW) (tons)**	**N0x (Kg)**	**SO2 ((kg)**	**N2O (kg)**	**PM (kg)**
		310	420	10	0.1	0.103	0.083	1.05	1.29	0.14
Results for Barcelona (S) — Valls (S)_S4										
Road	**Barcelona→Valls S S4**	**Distance (Km)**	**Cost (EUR)**	**Time (unit)**	**GHG CO_2 (WTW)**	**C02 emis-sions (WTW) (tons)**	**N0x (Kg)**	**SO2 ((kg)**	**N2O (kg)**	**PM (kg)**
		147	100	1.5	0.079	0.077	0.045	0.429	0.61	0.057

Tab. 24. Emissions for Scenario 4

Method 1						
	CO_2 (EUR)	N0x (EUR)	SO2 (EUR)	PM2.5 (EUR)	Cost of freight (EUR)	Total cost of emissions (EUR)
Matosinhos - PT→ Setubal - PT	2.5493	0.448	0.779	2.726	**354.47**	**6.50**
Setubal PT → Sagunto-S	1.75084	0.952	19.147	58.28	**975**	**80.12**
Sagunto-S → Barcelona-S	0.481	0.2324	4.305	7.524	**420**	**12.54**
Barcelona→Valls	0.37999	0.126	5.4483	5.358	**100**	**11.31**

Tab.25. Summary of the distance travelled vs costs of emissions by scenario S4

Method 2				
	Distance (Km)	**Cost of emissions by scenario (EUR)**	**Total cost of emissions (EUR)**	**Cost of freight (EUR)**
Matosinhos - PT→ Setubal-PT	361	115.52	**115.52**	**354.47**
Setubal PT → Sagunto-S	1317	39.51	**39.51**	**975**
Sagunto -S → Barcelona-S	310	114.7	**114.7**	**420**
Barcelona →Valls	147	4.41	**4.41**	**100**

those routes, and the distance travelled is very close. This supports the claim of environmental benefits when choosing sea shipping as a mode of transport.

In this scenario, different modes of transport were used, and Tables 24 and 25 summarise the total costs of emissions for each method. For the case of Method 1 (Table 24), for all considered routes, the costs of emissions are lower than the costs of freight, yet the results showed that sea transportation was considered as the mode with a higher cost of emission. This can be explained by the distance travelled, which means that for this scenario, if pollutants and their costs are considered, the possibility of using rail and road as the main alternatives for transporting goods may be considered.

Using Method 1 (Table 25), the route Matosinhos (PT) to Setubal (PT) had higher costs, followed by Setubal — Sagunto — Barcelona.

The results presented in this section aimed to assess and discuss the external costs of transportation, focusing on the environmental and social impact. The presented case summarises the impact caused during the transportation from Portugal to different countries. For most of them, companies should pay a price higher than the cost of transportation.

Since the demand for freight transport has been increasing worldwide, there is a need to develop initiatives to support transport companies in the process of decarbonisation. Nevertheless, several initiatives are ongoing. It is also important to highlight that companies cannot support the additional total external cost of emissions by themselves. Thus, this research brings together two approaches: the intermodality and calculation of the external cost of transportation as key elements to be considered by stakeholders, governments, and academics to draw attention to the negative impacts of transportation.

Conclusions

As an essential economic activity, freight transport experienced significant growth over the decades. However, questions should be asked regarding the impact of these activities on the environment and society. From this perspective, it is urgent to develop initiatives to support companies operating in this area, overcome these barriers, and operate in a greener and more sustainable way.

The work presented in the article aimed to bring together two main approaches that need to be better discussed to support logistics companies and stakeholders in the decarbonisation of the sector, i.e., intermodal transportation and the internalisation of the external transport costs. The proposed model is linked with the current literature that calls attention to the need to use intermodality in transportation as a key element to minimise the impact on the environment, as well as the importance of economically quantifying transportation costs.

The literature showed that intermodal transport is an option that supports companies in delivering goods and reducing their carbon footprint. This work used a case study to illustrate the role of intermodality in reducing CO2 emissions and contributing to sustainable transportation. Three routes were selected, and a furniture company was used as a case study to study four different scenarios.

The scenarios were analysed using the DHL Carbon Calculator platform to calculate the kilometres and the emitted CO2 content. The results determined the ideal scenario for each route. The evaluation of the remaining variables also allowed for the choice of the best scenario. For example, the cost of transport increases with the growth in the number of kilometres and if several types of transport modes are combined. The evaluation of the remaining variables also allowed for conclusions regarding the choice of the best scenario.

It is important to highlight that the emissions are directly related to the load weight and the mileage travelled. This research draws attention to the importance of using the concept of intermodality as a particular and relevant strategy in supporting companies in the transition to a means of sustainable transport.

In this research, the model proposed to measure emissions was used due to the need for a comprehensive cost analysis to further assess the impact on the environment. Based on the results, a set of key policy measures were identified:

- Regarding the internalisation of the external cost emissions, the findings showed that for the selected scenarios, there is a different pollutant emitted during transportation, which means that the negative impact on human health and the environment is evident.
- Findings also indicate that considering the "user pays principle", these impacts should be paid. The results also indicate the total costs of emissions by route, which is higher than the value paid for the freight.
- The findings also suggest a better discussion and application of the presented method. It would be an important tool to disseminate the environmental and social concerns between freight transport companies.

For future works, some adjustments in the methods can be made, including an analysis of different routes. Regardless of the potential contribution of this research, some limitations need to be highlighted, such as the difficulty in assessing availability and schedules in the transport used and the need for a detailed economic cost analysis for different scenarios considering intermodality. Despite being a simple approach, the achieved results could offer an important lesson for companies, logistics operators, and local governments in developing strategies to support companies in the transition from unimodal to intermodal transportation.

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