The Impact of a New Container Port on the Greenhouse Gas Pollution

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Abstract

Background: Large vessels that call at European ports will have to pay for their CO2 emissions from transporting cargo that enters or goes from a European port since January 2024. The costs will increase with increasing global trade. This results in a higher pollution level, including greenhouse gas (GHG) emissions like CO2. **Methods/ Approach:** Based on the gravity model embedded in a global supply chain, we developed a model to evaluate maritime transport pollution in case a new, sufficiently large container port becomes operational. Additionally, we consider how lousy railway connections to European customers increase transportation costs and pollution. **Results:** The approach to the well-connected sequences of gravity models in the intercontinental maritime chains evaluates the differences in quantities of cargo between ports when a new port is opened, and the waiting time does not change. We also highlight that poor rail connections can reduce this positive effect. **Conclusions:** We showed how it is possible to estimate the optimal capacity of a new port with a multi-level gravity model and how this would affect the pollution around the port and on the routes from the port to the final consumers.

Keywords: gravity model; supply chain; seaport; pollution; intercontinental transport; container terminal; railway; CO2 emissions

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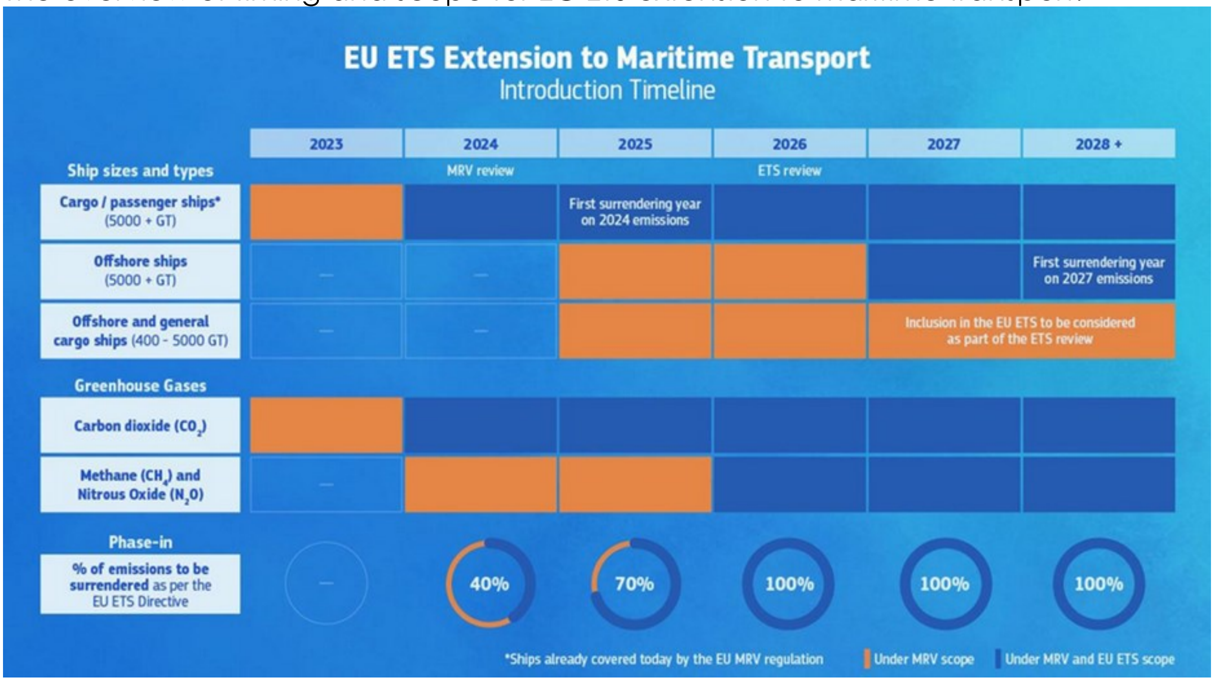
Introduction

The European Union Emissions Trading System (EU ETS), including the MRV (monitoring, reporting and verification) of vessels' emissions, is becoming one of the EU's main tools for reducing greenhouse gas emissions in maritime transport. The Commission has adopted several implementing acts and directives that determine the necessary rules and methods for the system's successful operation to ensure the timely inclusion of maritime transport in the EU ETS as early as January 2024 (European Commission, 2024).

Sea routes and ports strongly impact pollution, especially with exhaust gases. For example, the results of Barberi et al. (2021) demonstrate the contingency between emissions and port infrastructures and show how proper investments can help reduce pollutant emissions in ports and maritime transportation in general. Port emissions are generated by manoeuvring and waiting in lines, including loading and unloading of ships, onshore operations using energy for loading, unloading, and warehousing cargo, and port vehicle traffic. Barberi et al. (2021) reported that estimating emissions in ports can be tricky due to the multitude of co-existing sources. The exhaust emissions from ships in maritime transport are calculated using activity-based and fuel-based methods.

Figure 1
The overview of timing and scope for EC ETS extension to maritime transport.



Source: European Commission, 2024

In our paper, we shall assume that the fuel structure and activity-based structure on the lines from other continents to Europe and from Europe to other continents do not change and that only the length of all sea routes and, therefore, the time spent on routes and in ports is reduced by investments and operations of a new port. The exhaust emission in the ports will be calculated as in Barberi et al. (2021), considering the same structure of activities as in the Chinese port that is also on the main intercontinental road of vessels (see Bogataj et al., 2024). The paper is an extended version of the paper presented at the SOR 2023 conference (Bogataj, D., & Campuzano-Bolarín, 2023).

The paper consists of six sections. After the short literature review in the Introduction, the method to evaluate the location advantages of a new port for international cargo is presented in the second section. The method of calculating CO_2 and other emissions in case of additional ports is presented in the third section. The fourth section describes challenges for equalising technical standards on Spanish and other European railways. The last section gives the conclusions and some directions for further study.

Literature review

Gravity models (GMs) have been known in social science since 1963 (see the literature review of Bınová, 2015), but as a sequence of sub-models in a model of the supply chain was presented first in 2018 (see Table 1). The idea of a three-stage sequencing of GM is given only in Bogataj et al. (2022, 2024). The articles of Bogataj et al. also tie all gravity models together well. The Web of Science Core Collection (WoS) found the first article linking the topics of "supply chain" (SC) and the "gravity model" (GM) only at the beginning of the second decade of this millennium, and only 41 articles followed the first publication. Among them, only three papers include the topic "maritime transport" to the topic "supply chain" (Chang et al., 2021; Gani, 2021; Randrianarisoa and Gillen, 2022). In the basic approach, the formulation of GM is as follows:

$$T_{ij} = \alpha P_i P_j / d_{ij}^2 \qquad (1)$$

where T_{ij} is the flow between origin j and destination i and d_{ij} is the distance between the origin and destination, P_i and P_j are the sizes of populations in the destination and origin. In some recent papers, authors replaced P_i and P_j by gross domestic product GDP_i and GDP_j and later by logistics quality indicator (M) as the product of the logistics capability parameter τ_i and the logistics volume L_i ($M_i = \tau_i L_i$ and $M_j = \tau_j L_j$) of hubs, capturing reliability, responsiveness, assurance, empathy, and tangibles. However, power in such models is still equal to 1 or at least symmetrical in many papers (Wei and Lee, 2021). In recent papers, the GDP_i was replaced by production quantity Q_i and GDP_j by attractiveness A_j of a port:

$$T_{ij} = \alpha Q_i^{\beta} A_j^{\gamma} / d_{ij}^{\delta} \qquad (2)$$

We will say that (2) is the basic equation also if Q and A are replaced by GDP_i, $\tau_i L_i$ or P_i . In the models of supply chains except by Bogataj et al. (2022, 2024) and Randrianarisoa and Gillen (2022), the distance d_{ij} has remained geographical. However, in papers considering pollution in a supply chain, like in Randrianarisoa and Gillen (2022), we can find first explanations why it is better to replace geographical distance (road, train, or Euclidean distance) with the time-consuming distance in sea routes and in waiting lines in a port, like in some GMs of population migrations and commuting (Drobne and Bogataj, 2014, 2015, 2017, 2020, Bogataj and Drobne, 2011, Drobne et al, 2011, Janež et al., 2016, 2018). The success of container transport is due to the reduction in the duration of port calls, which means the reduction of waiting and service time in ports (Slack et al., 2018).

Although vessels now spend less time in port than at sea, it is still a cost and pollution factor. Randrianarisoa and Gillen (2022) studied only one stage of GM, which cannot answer the questions on the impact of a new node in a sea chain. Their paper proposes a novel way to reduce sulphur emissions in international transport by focusing on the role of logistics improvements and vessel size. When transportation intensity increases, pollution is calculated by adding a new number of vessels. The basic GM with the modified factors is extended. There are no solutions about where to locate a new node to reduce pollution. GDPs per capita and not GDPs itself at origin and destination have been two basic variables in the cited paper. The accessibility factor is divided into the natural and created part, where the geo-distance is part of this structure. The time spent factor is added extra and therefore is less fit for our purposes. Only four articles in WoS deal with a supply chain with two consecutive sections (Table 1).

Table 1
Articles in WOS with topics »supply chain" and »gravity model" where authors also mention maritime transport or any other sea transport in two or more stages

Year	Author	Mode	Purposes and methods	Stages
2018	Liu et al.	Any	A food-based virtual blue, green, and grey water network is built here. The gravity model and linear programming optimisation were used to model the interprovincial trade of Chin. There is no question about the location of a node.	2
2018	Wei et al.	Rail and road transport	Two-stage GM of inland logistics refers to the connectivity between the Maritime Silk Road and the Silk Road Economic Belt. There is no question about where to locate a seaport.	2
2021	Wei and Lee	Railway Express	This study employs a hybrid method with an improved entropy-weighted TOPSIS, a matching logistics capability and demand model, and a cross-border logistics gravity model considering the Silk Road Economic Belt. There is no question about where to locate a node or the impact of its capacity.	2
2022	Bogataj et al.	Vessel	The article shows how to improve the supply chain if a new port is included in the supply of perishable goods.	3

Source Web of Science

According to the findings of Nordås and Piermartini (2004), the log expression of GM of cargo (one-stage model) from j to i (M_{ij}) can be presented as follows:

$$M_{ij} = a_0 \cdot y_i^{a_1} \cdot y_j^{a_2} \cdot d_{ij}^{a_3} \cdot border_{ij}^{a_4} \cdot lang_{ij}^{a_5} \cdot island_{ij}^{a_6} \cdot landlock_{ij}^{a_7} \cdot (1+t)_{ij}^{a_8} \cdot infr_i^{a_9} \cdot infr_j^{a_{10}} \cdot T_i^{a_{11}} \cdot T_j^{*\,a_{12}} \cdot lat_i^{a_{13}} \cdot lat_j^{a_{14}} \quad (3)$$

where the first three variables give a relatively high correlation coefficient, and according to the high correlation of time distance with other variables (Rietveld et al., 1999), the other variable could be included in the distance if we replace the geographical distance d_{ij} with the time-spending distance τ_{ij} (time assumed in direct proportion to distance). In this case, we leave the velocity factor v, which is equal in all directions, at the intercept: $a = v \cdot a_0$. In this case, we may write:

$$M_{ij} = (a_0 v) \cdot y_i^{a_1} \cdot y_j^{a_2} \cdot \tau_{ij}^{a_3} \rightarrow lnM_{ij} = \ln a + a_1 \ln y_i + a_2 \ln y_j + a_3 \ln \tau_{ij} \quad (4)$$

Methodology for evaluation of port advantages

The starting point of this research is the work conducted by Nordås and Piermartini (2004), who estimated the powers (regression coefficients of linearisation) in maritime and road transport as given in Table 2. Regarding high R^2 for regressions in Table 2, we used these values to evaluate the potential flow of containerised cargo through Cartagena port when constructed, and flows will optimally adapt to the new network possibilities.

Table 2
Value of main regression coefficients in the gravity model (p < 0.01).

Regression coefficient	Indicator	Road infrastructure	Maritime infrastructure
a1	GDP importer	0.94	0.80
a2	GDP exporter	1.12	0.91
a3	distance between I and j	-1.22	-0.71
adjusted R2		> 0.65	> 0.70

Source: Nordås and Piermartini (2004)

Continuing the procedure like in the article by Bogataj et al. (2024), in this paper, we added the waiting time for cargo unloading from vessels and loading on trucks as τ_k ; when revised (2) to (5):

$$M_{ki} = a \cdot y_k^{0.80} \cdot y_i^{0.91} \cdot (\tau_{ki} + \beta\tau_k)^{-0.71} \quad (5)$$

and for road transport from port k to EU city l:

$$M_{lk} = b \cdot y_l^{0.94} \cdot y_k^{1.12} \cdot (\tau_{kl} + \gamma\tau_k)^{-0.71} \ . \quad (6)$$

In (5) and (6) β and γ are the proportionality coefficient between the costs of the hour of waiting and unloading or loading in the port and the hours of sailing of the container ship and truck, respectively, per unit of cargo. We may take the average waiting and service time of ships at ports of some EU and neighbouring countries from UNCTAD (2018) and Slack et al. (2018), wherein port call and performance statistics, including time spent at ports, are given. In our numerical example, we used $\beta = 1$ and $\gamma = 1$. World merchandise trade volume 2000 - 2021, including projections, are available at WTO (2021). Sea time distances between the biggest ports from a list of ports on other continents and EU ports are available at the World Shipping Council (2021). We took the data for the year 2021 and their time series. The distances between EU central places and EU ports are available at Google Maps. Time distances for trucks have been calculated under the assumption that the average speed of trucks is 70 km/h.

The average waiting and service time of ships at ports of the EU countries is grouped in our paper in three groups: group I: 0.3-0.6 days: Gibraltar, Norway, and Denmark; group II: 0.61-0.8 days: Croatia, Sweden, Lithuania, Slovenia, Spain, Portugal, Poland, Finland, Latvia, France Netherlands; group III: 0.81+ days: others. 13 the biggest ports have been considered. In Table 3, we calculated the average time distances of 1 twenty-foot-long container (TEU) in the case of $(\boldsymbol{\tau_{lk}} + \boldsymbol{\tau_k})$ o the EU continental member states (l) and the leading 12 EU ports (k), in case of being transported by trucks. From Table 3, based on the GM approach, the optimal cargo sharing between ports in 2039, if the port of Cartagena will be completed by then, is calculated as given in Table 4. Cartagena as the potential port was added.

Table 3
Time distance in hours between metropolises in EU continental member states and the main EU ports transported by truck*.

Port / City	CA	HB	BH	ANT	ZB	VA	AL	BA	LH	MA	RT	GD	PI
Vienna	38	17	17	19	20	33	44	30	24	24	21	29	29
Brussels	31	13	12	5	6	27	35	22	10	18	7	24	35
Sofia	45	32	32	35	36	43	53	38	40	40	36	30	33
Prague	37	13	14	17	19	33	43	27	21	23	17	16	32
Berlin	38	9	10	15	16	35	44	30	35	26	14	13	34
Copenhagen	44	11	13	19	21	40	48	35	24	31	18	19	43
Tallinn	61	34	35	40	41	57	68	53	44	48	38	23	54
Athens	58	41	41	44	45	55	65	50	47	45	44	40	30
Madrid	10	36	36	27	26	9	13	13	23	20	28	47	41
Helsinki	65	35	38	44	45	63	73	57	50	53	43	27	60
Paris	27	18	18	10	10	23	30	18	8	15	11	29	35
Zagreb	35	22	23	23	24	32	41	27	27	21	24	22	25
Budapest	40	20	21	23	25	36	45	31	27	25	24	19	29
Rome	32	28	29	26	28	28	38	24	27	18	28	32	13
Riga	55	28	30	34	36	53	63	48	40	43	33	18	50
Luxemburg	28	14	13	8	9	25	35	20	12	16	10	23	31
Vilnius	53	25	26	30	32	48	58	44	36	40	30	14	45
Amsterdam	34	11	10	7	8	29	37	25	14	21	6	21	36
Warsaw	38	17	18	23	24	41	51	36	28	31	22	10	38
Lisbon	17	40	40	32	32	17	13	21	28	26	34	50	47
Bucharest	53	33	33	36	37	48	58	43	40	38	37	31	40
Stockholm	53	20	22	29	30	50	58	44	34	40	28	27	51
Ljubljana	33	21	21	21	23	29	40	25	24	19	22	22	23
Bratislava	38	18	18	21	23	35	45	30	25	26	22	16	29

CA-Cartagena; BH-Bremerhaven; ANT-Antwerp, ZB-Zeebrugge; VA-Valencia; AL-Algeciras; HB-Hamburg; BA-Barcelona; LH-Le Havre; MA-Marseille; RT-Rotterdam; GD-Gdansk; PI-Piraeus
*Source: Authors' work based on Google Maps. *Waiting time in ports is added.*

Table 4
Expansion of the annual cargo handling by 2039 in the main EU ports [in 10^6 TEU].

If Cartagena Port is built						
Cartagena	Hamburg	Bremen h.	Antwerp	Zeebrugge	Valencia	Algeciras
7,9	5,5	9,2	-0,6	11,1	3,4	1,6
Barcelona	Le Havre	Marseilles	Rotterdam	Gdansk	Gioia Tauro	
6,1	9,5	9,2	0,1	8,9	5,1	
If Cartagena port will not be completed						
Cartagena	Hamburg	Bremen h.	Antwerp	Zeebrugge	Valencia	Algeciras
0,0	6,1	10,3	0,0	12,4	3,8	1,8
Barcelona	Le Havre	Marseilles	Rotterdam	Gdansk	Gioia Tauro	
6,8	10,6	10,2	0,1	9,9	5,7	

Source: Authors' work.

In Table 4, the data are in 10^6 TEU, as logistics and shipping companies usually measure the quantity of cargo. They load up to 24000 kilograms (24 metric tons) of cargo in a TEU. An empty container weighs 2280 kilograms (2.24 metric tons). Hence, the total weight of a fully laden twenty-foot container will be 26280 kilograms (26.28 metric tons. Bogataj et al. (2024) presented detailed methods and data derivation based on the sequential GM models of global supply chains.

Potential increase of yearly emissions in the EU's biggest ports by 2039 if Cartagena port would be completed

The optimal allocation of cargo along individual routes on the graph has been discussed countless times from the point of view of economic efficiency but less so from the point of view of pollution. However, the development and application of gravity models for these purposes were also less frequently used in these studies.

Using the GM approach, Oesingmann (2022) studied the impact of the EU ETS on aviation demand; Hintermann and Ludwig (2023) pointed to informational transaction costs that increase when trading across national borders, also showing the usefulness of the GM, but not exposing the maritime transport. Bart (2011) has shown that municipal emissions can be calculated as a share of total national road transport emissions with the support of a GM. Pothen and Hübler (2018) studied climate and trade policies, focusing on their interactions, and the GM approach was also explored. In WoS, however, we do not find any authors who would connect the pollution problem in maritime transport, or only in ports, with the newly introduced EU ETS in naval affairs. In our paper, following the data in Table 4, the expected pollution in the biggest EU ports can be estimated using the GM approach.

Let us take for the EU the biggest ports with the same structure of emissions of nearly 125,000 ships, like Qingdao in 2016 (Sun et al., 2018), where container ships' pollution is approximately 2.8/5. [NO_x, CO, HC, CO_2, SO_2, $PM_{2,5}$] = 10^3[16.7, 1.7, 0.7, 1,275, 11.9, 0,96].

Table 5
Increase the yearly emissions in the EU, the most prominent ports, by 2039 if the Cartagena port is completed and technology does not change [ton].

	Cartagena	Hamburg	Bremen h.	Antwerp	Zeebrugge	Valencia	Algeciras
NOx	7798	5415	9034	-579	10888	3355	1609
CO	805	559	932	-60	1124	346	166
HC	331	230	383	-25	462	142	68
CO2	596342	414064	690857	-44257	832629	256540	123019
SO2	5556	3858	6437	-412	7757	2390	1146
PM25	447	310	518	-33	624	192	92
	Barcelona	**Le Havre**	**Marseilles**	**Rotterdam**	**Gdansk**	**Gioia Tauro**	
NOx	6023	9368	8995	78	8760	5032	
CO	621	967	928	8	904	519	
HC	256	398	382	3	372	214	
CO2	460571	716361	687857	6001	669854	384810	
SO2	4291	6674	6409	56	6241	3585	
PM25	345	537	516	4	502	288	

Source: Sun et al. (2018) and own calculations.

Here, 1 TEU will be, on average, equal to nearly 30 metric tons. The yearly emission in 2039 (when the Cartagena port would be completed) in the EU's biggest ports will increase for the values in Table 5 if the technology does not improve. The realised data forecasted in Tables 4 and 5 will be subject to the MRV procedures established inside the European Emissions Trading System, as described in the Introduction.

Challenges for equalising technical standards on Spanish and other European railways

Since the average weight of a 20 FT TEU is about 2,500kg (a container 20 feet long, 8'0" wide, and usually 8'6" high), we can calculate the expected quantity of CO2 yearly emissions if the average reference emissions amount to 52.7 gram of CO2 per tonne-kilometre (gCO2/km), as reported by Transport & Environment 2021.

Table 6
Yearly CO_2 pollution on roads by trucks to the countries potentially using the Cartagena port by 2039. (Annual capacity in 10^6 kg)

Country	Distance [102 km]	Ml. C [103 ton]	Pollution [ton] of CO2	Country	Distance [102 km]	Ml. C [103ton]	Pollution [ton] of CO2
Austria	24	450	56,916	Italy	20	2,232	235,253
Belgium	19	667	66,787	Latvia	36	27	5,122
Bulgaria	30	65	10,277	Lithuania	34	42	7,526
Croatia	22	77	8,927	Luxembourg	18	110	10,435
Czechia	23	272	32,969	Netherlands	21	1,005	111,223
Denmark	28	305	45,006	Poland	30	602	95,176
Estonia	39	4.5	4,624	Portugal	9	580	27,509
Finland	40	152	32,042	Romania	30	182	28,774
France	16	3,665	309,033	Slovak Rep.	25	170	22,398
Germany	25	3,495	46,0466	Slovenia	21	72	7,968
Greece	34	135	24,189	Spain	4.5	4,997	118,504
Hungary	25	170	22,398	Sweden	34	375	67,193

Source: EUROSTAT 2022, Via Michelin, 2024 – to the metropolis (rounded).

The results are given in Table 6, which shows that the yearly pollution of transporting the cargo from the port of Cartagena to individual EU member states would be approximately 1,8 million tons. It is approximately 1/3 of annual CO2 emission in the port of Cartagena, as given in Table 5. In equation (5) and other calculations, we assumed that cargo transport from European ports to EU member states will only be carried out by road. While this is almost essential for perishable goods, heavy, non-perishable cargo is more suitable for rail transport. Carried out by the road, *the average emissions amount to 52.7 grams of CO_2 per tonne-kilometre (gCO2/tkm) of cargo. These data constitute the overall baseline for the following year's* (2025) *emissions targets of a 15%* reduction in Europe (Transport & Environment, 2021).

Regarding the relative costs of pollution per tonne-kilometre transport of cargo, we can also expect, in the future, that the cost of rail transport will not exceed a quarter of the cost of road transport (Banfi et al., 2000). For rail transport, it is often expected to present only 10% of costs caused by road transport if there are no specific obstacles in the way. However, Spain has problems here, as the standards of its railway networks (the electrification technology and the track gauge) are incompatible with other European standards. It causes problems at the borders with France.

According to the EU Directives (European Commission, 2013), considering Regulations No 1316/2013 and 1316/2013, The freight corridor RFC6, which connects Southwestern European countries with Eastern European countries, belongs to the TEN-T network as defined (European Commission, 2013). RFC6, as all the lines of the TEN-T Corridors Core Network must be standardised regarding gauge (or mixed gauge) by 2030, it should have 25 kV AC electrification, a single European signalling system and train speed control ERTMS (European Rail Traffic Management System). The Global System for Railway Mobile Communications (GSM-R) was also introduced for TEN-T.

Figure 2
Cartagena port on the RCF6 corridor goes through Spain and France, continuing to Kyiv.

Source: Mediterranean Rail Freight Corridor (2024) and authors elaboration, AJOT (2023).

The Cartagena port would become one of the most important nodes inside the Mediterranean Corridor (MC), the longest in the European Union. MC ranks second in freight transport and serves countries representing 18% of the European population, but it is easily linked to other EU corridors. We calculated the advantages of cargo being transhipped at Cartagena for the case of road transport only, leading to the optimal solution, as given in Table 5. The Rail Freight Corridor 6 (RFC6), which belongs to MC, has two separate routes: the Central Mediterranean Corridor and the Coastal Mediterranean Corridor (see Figure 2). Cargo on these corridors must cross the French border if it continues to other European countries. RFC6 is the most connecting freight corridor, linked to freight corridors RFC1, 2, 3, 4, 5, 7, 10 and 11.

Crossing the border from Spain to France is costly due to the differences in the electrification technology and the track gauge that requires special transhipments. When the new EU technological standards for railways are also achieved in Spain, the advantage of the port of Cartagena over other ports, calculated based on the sequential gravity models on the global supply chain, will be definitive for all modes of transport.

Conclusion

To regulate the rising environmental impact of sea transport, the EU also integrated ports into the European Emissions Trading System (EU ETS) in 2024. Vessels' CO_2 emission is now included in the EU ETS, which is essential for reducing greenhouse gas emissions in maritime transport. That is why it is necessary, when deciding on constructing a new port or expanding old ports in the intercontinental goods transport network, to assess the expected pollution in the ports and the routes to the final consumer.

The optimal allocation of cargo along individual routes regarding pollution was rarely studied, especially in case of a development or application of gravity models. We found only four articles in the WOS that include both the "gravity model" and "Emission Trading System" (Oesingmann, 2022; Hintermann and Ludwig, 2023; Bart, 2011; and Pothen and Hübler, 2018). They studied environmental trade policies, and the GM approach was also used. However, nobody considered maritime transport and port pollution.

In the article, we showed how it is possible to estimate the optimal capacity of a new port with a multi-level gravity model and how this would affect the pollution around the port and on the routes from the port to the final consumers. In particular, we focused on the problem of uncoordinated technical standards of railways in Spain and elsewhere in Europe, which raises the cost of rail transport. The calculations assumed that the structure of ships in Mediterranean liner transport is similar to that of ships in Chinese ports on the same intercontinental line. When the technical standards are fulfilled, direct transport could reduce pollution on transport routes by as much as 70%-90%.

This paper has not considered future technical improvements that could influence pollution, which could be the subject of further research. From the data collected and displayed, it is possible to study the impact of pollution on health, the built and natural environment, and climate change, which is still a wide-open field of research.

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