External costs as a tool to promote Short-Sea-Shipping

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ABSTRACT: The dissertation comprises, firstly, a literature review on methods to evaluate emissions and external costs of transportation. The focus will be the evaluation of the competitiveness of waterborne transportation. A review of current externalities internalization levels for the different transport modes in EU countries was included by reviewing current GHG and other transport externalities policies established by IMO and the EC. The new version of the software Sustainability Analyst (SA) includes the habitat damage costs. The software is also able to calculate external costs for varying numbers of transport chains for different pairs O/D, properly identifying possible transport chains for a specific destination. The results of emissions and external costs provided by SA are also validated by using alternative software and online calculators, even if the websites available are limited. The software is applied to study several scenarios: current and expanded scope of intermodal routes over uncertainties about cargo utilization factor; Diesel and Electric freight railway service in operation in the Atlantic corridor; and expanded SSS service to the West Mediterranean. A comprehensive set of maps is developed to illustrate the regional preferences as regards different alternative transport chains and modal splits estimated for multiple pairs of Portugal-NUTS2 under different scenarios. An increased cargo utilization factor reduced external cost in the preferable route by 22% and the adoption of new intermodal routes represented a reduction of external costs by 20%. By computing also internal costs, external costs are shown to be only 29% of the total cost, limiting the increase in the competitiveness of intermodal routes related to a better environmental performance.

1 INTRODUCTION

Current extreme weather events have arisen the importance of consistent international climate actions to contain the climate change. Emissions of greenhouse gases (GHG), i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases are the major responsible for the Greenhouse effect. Although the Earth's temperature rise is a natural phenomenon, the excess of anthropogenic emissions has accelerated the heating process. The source of GHG emissions showed that the transportation sector constitutes 14% of global emissions in 2010 (EPA, 2010). Freight and passenger transport emission shares increased to 29% in 2018 in the European Union (EU) and the road mode and marine transportation are responsible for 5% and 4% of total economy-wide emissions in 2018 (ICCT, 2019). Scientific research shown that other gases are associated with harmful to human health and the environment, namely sulphur oxides (SO_X), particulate matter (PM), and nitrogen oxides (NO_X). Therefore, the need for environmental regulations in the transportation sector for the sake of meeting climate targets.

Proposed at the UN Climate Change Conference (COP21) in 2015, the Paris Climate Agreement aims to reduce GHG emissions to contain the global temperature rise to 2°C above pre-industrial levels through a review of parties' commitment every 5 years and climate financing funds to developing countries (UN, 2022). As the third-largest emitter in the world, the EU has also presented the European Green Deal in 2019, a core strategic plan to turn Europe into the first climate-neutral continent by 2050 (EC, 2019b). In July 2021, the 'Fit for 55' package of actions announced new directives and financial endowment programs in most economic sectors to achieve European Green Deal goals – the net GHG emissions levels reduction not less than 55% compared to emission levels registered in 1990; at least 32% share of renewable energy; and 32.5% energy efficiency improvement by 2030.

Since 2018, the International Maritime Organization (IMO) has been providing important contributions to the global fight against climate change (UN, 2015) by the Amendments to Annex VI of the 1997 MARPOL Protocol. For instance, the Energy Efficiency Design Index (EEDI) required a minimum energy efficiency level per capacity mile in ship design. In June 2022, the 78th section of the Marine Environment Protection Committee (MEPC 78) proposed the Energy Efficiency Existing Ship Index (EEXI) to ships in operation as the mass of CO_2 emissions per ship's capacity and speed, criteria required in the periodical survey in 2023 (DNV, 2020). Under the same Annex, the Ship Energy Efficiency Management Plan (SEEMP) propose ways to shipping companies to keep track of emission levels during the ship's operational phase considering cost aspects (IMO, 2020). From 2024, the Carbon Intensity Indicator (CII) calculation will be annually required for ships engaged in international transport over 5,000 GT, using the SEEMP Part III as a document to evaluate the shipowner plan to improve the CII for the following three years (DNV, 2022).

Another effort for reducing air pollution from ships carried out by IMO was the creation of Emission Control Areas (ECA), designate sea areas where the concentration of sulphur oxides (SECAs), or nitrogen oxides (NECAs) is limited by the fuel quality. Nowadays, SECAs are distributed on the North American coast, Baltic Sea, North Sea, and the United States Caribbean Sea areas, limiting the fuels sulphur content to 0.1%. In June 2022, MEPC 78 approved the extension of SECA to the Mediterranean Sea, coming into action after December 2022. In international waters outside ECA, the sulphur content is controlled since 2005, and the requirement constantly evolved from 4.5% sulphur content in 2005 to 3.5% in 2012, and a significant reduction to 0.5% in 2020 under regulation 14.1.3 of MARPOL Annex VI (IMO, 2016), but still five times greater than inside ECA.

The efforts for the decarbonization of shipping through the 'Fit for 55' package will also affect the international navigation due to the EU extra-territorial trade and the short implementation time of such actions (Maersk, 2022). Among other four actions, the EU-ETS Directive will be partially introduced, allowing ships to handle 20% of the verified emissions in 2023 with a gradual percentage until the total reported emissions in 2026. The FuelEU Maritime Regulation, in addition, promotes the use of renewable and low-carbon fuels in ships (Hellenic Shipping News, 2022c), the Alternative Fuel Infrastructure Regulation regulates LNG bunker availability by 2025 and shore electrical supply by 2030; and the Energy

Taxation Directive establishes taxation over the use of conventional fuels.

The concept of external cost is "a cost or benefit imposed on a third party who has not agreed to incur that cost or benefit" (Pigou, 1920). When the range of negative effects is considered in an intermodal chain, externalities can be monetized from different perspectives. Without full internalization, shipping companies are subjected to losing the competition to more polluting modes to cope with new environmental regulations. For instance, in April 2022, the European Commission (EC) approved €60 million in funding for encouraging Spanish maritime freight transport in exchange for the road mode through the Recover and Resilience Facility plan. The scheme involves direct grants to road haulers to move to SSS, motivated by the argument that external costs from transportation could be reduced by using maritime transport (EC, 2022b). By the same fund, the Spain has received €120 million in incentives for the railway transportation infrastructure (EC, 2022a) with the objective of promoting freight transport substitution, aiming an increasing use of sustainable modes of transportation. Emission reductions and modal shift policies must rely on suitable numerical tools capable of assessing intermodal transport chains on a door-to-door basis, considering both internal and external costs of transportation.

This thesis's purpose is to assess the potential of external cost internalization for encouraging SSS in Europe and analyze the impact of new intermodal chains in the decision-making process, considering or not environmental issues. The software Sustainable Analyst (SA) responsible for computing emissions and external costs was modified with the purpose of apply updated methods and enhancing the user usability. The numerical tool was adapted for running different instances of the transport network from Porto to a vast geographical scope of destinations in Europe.

This paper is structured into seven sections: a literature review about emission calculation methods and external cost internalization strategies in section 2; the methodology applied in the numerical tool in section 3; method validation in section 4; presentation of the geographical scope and technical characteristics of the vehicles in section 5; the numerical results are presented in section 6; and conclusions and future works are indicated in section 7.

2 LITERATURE REVIEW

2.1 Air pollution estimation methods and regulations

Air pollutant emissions methods are divided into primary methods (direct measurement at the source point) and secondary method (emission factors and modeling). Direct measurement offers the advantage of lesser uncertainties, but it's a more expensive method focused on a specific source of emission. Emission factors are more commonly applied to obtain input data for assessment studies due to its simplicity and availability (Fan & al., 2018). However, increasing uncertainties arise from emissions deterioration over the useful life of the vehicles, variation among identical engines, and the impact of cold and hot start engines (JCR, 2017).

Concerning GHG emissions in road mode, extensive literature can be found in (Clairotte & al, 2020; Zhang & al, 2021), presenting Well-to-Wheel CO_2 equivalent, N_2O and CH_4 exhaust emission factors from L-category, light-duty, and heavy-duty vehicles based on measurements carried out in laboratory between 2009 and 2019. A review of literature also presented in (Speirs & al, 2020) concerns a transition from Diesel to natural gas fueled trucks in terms of GHG emissions and costs involved, and further pollution prevention can be found in (Inkinen & Hämäläinen, 2020). Including other air pollutants, PM, $CO_{2,}$ and NO_X emission factors based on portable emissions measurement systems were investigated in (Dhital & al, 2021) to investigate the effect of vehicle attributes, driving behavior, and road grade. The dispersion of PM produced by HDV fuel combustion, and the number of deaths attributed to the PM emitted were analyzed in (Teixeira & al, 2020) in the Brazilian transport system in the transition to LNG.

Standard limits and fuel quality regulations established by the EC on fuels commercialized in Europe are referred as Euro I to VI standards for new heavy-duty diesel engines equipped with compression ignition or positive ignition natural gas or liquefied petroleum gas (LPG) engines. For Diesel engine trucks, (DieselNet, 2022a) summarizes the emission standards present in previously mentioned regulations in two different testing requirements over CO, HC, NO_X, PM, PN, and smoke. For fuel-based air pollutants, $CO_{2\text{-eq}}$ and SO_X emissions were obtained by using the sulphur content present in the Diesel fuel. Directive 2003/17/EC established the EN590 standard in 2004, establishing sulphur limits of 50 ppm (Euro 4) and 10 ppm (Euro 5).

Compared to only-road transportation, recent publications show rail transportation as a more environmental-friendly mode. The impact of increasing speed on GHG emissions in high-speed rail (HSR) lines has also concluded important contributions to emissions during construction and operation phases (Jiang & al, 2021; Lee & al, 2020). A review of estimation such methods for computing emissions from rail freight transportation was analyzed in (Heinold, 2020), in which five GHG emission models were evaluated - two from the MEET project, ARTEMIS model, EcoTransIT World model, and Mesoscopic model.

Rail transportation emissions are regulated by directives and regulations from the EC for engines used in new non-road mobile machinery (NRMM). Directive 97/68/EC and five amending Directives published between 2002 and 2012 defined Stage I–IV requirements for Diesel engines. Regulation 2016/1628, which replaces Directive 97/68/EC and its revisions, establishes emission criteria for all types of compression ignition (diesel) and positive ignition mobile nonroad engines starting with Stage V. Specifically for rail traction engines above 130 kW, Stage III A, and III B standards have been adopted for the propulsion of railroad locomotives and railcars. Later, the regulation was expanded and simplified for the propulsion of rail locomotives and railcars of any power rating and any type of ignition in Stage V emission standards. The limits for rail transport for CO, HC, NO_X, and PM are summarized in (DieselNet, 2022b).

Regarding ship emission, publications mainly focused on non-GHG gases can be found in (Bremnes, 1990) and (Corbett & al., 1999). A bottom-up estimate of fuel consumption and vessel activity for international fleets was studied by (Corbett & Koehler, 2003) to address some uncertainties present in previous inventories and (Endresen & al, 2003) and (Endresen Ø. , 2007) focused on global emission inventories of $NO_{X,}$ SO_2, CO, CO_2, and VOC. Additionally, a historical review between 1950-2001 of emissions from international shipping was carried out by (Eyring & al, 2005).

Among recent emission frameworks, the Ship Traffic Emissions Assessment Model (STEAM) is the basis of current IMO GHG Studies method for evaluation of the exhaust emissions of marine traffic based on data provided by AIS. Since 2000, IMO publishes studies about the situation and forecasting of global carbon emissions (IMO, 2000; IMO, 2009a; IMO, 2014), addressing data quality challenges and uncertainties in both top-down and bottom-up techniques, in which further discussions can be found in (Psaraftis & Kontovas, 2020; Psaraftis, 2019). In line with MEPC 74th session in 2019, the Fourth IMO GHG Study (IMO, 2020) provides an inventory of GHG and air pollution emissions from shipping for the period between 2021 and 2018 and presents emissions projections for the period between 2018 and 2050, applying a emission estimation methodology for gases regulated in the United Nations Framework Convention on Climate Change (UNFCCC).

Further literature reviews regarding emission factors in maritime transportation can be found in (Miola & Ciuffo, 2011), presenting a meta-analysis of research published until roughly 2011, and (Nunes & al, 2017), examining 26 activity-based studies published after 2010, including specifics on parameters. (Miola & Ciuffo, 2011) also conduct a critical examination of the current emission modeling methodologies and data sources. The EMEP/EEA inventory Guidebook (EMEP/EEA, 2019) also covers emissions of CO_2, CH_4, N_2O, CO, non-methane volatile organic compounds (NMVOCs), SO_2, PM, and NOx emission factor databases extensively utilized throughout Europe (Grigoriadis & al, 2021).

More than 95% of inland ships are propelled by Diesel engines, with average motor age of 40 years (UBA, 2012), addressing negative effects from freight transport along rivers and channels. The applicability of modern alternatives for inland ship power systems, such as lithium batteries and hybrid powered ships (LNG and battery modulus), and abatement technologies (mainly scrubber and green fuel) was the focus of several studies. Many other strategies for reducing air emissions are related to regulatory and operational strategies, such as tripartite evolutionary game model that environmental governance to promote electric power (Xu & al, 2021) and a heuristic algorithm for solving the lock scheduling problem to minimize CO_2 emissions (Golak & al, 2022).

2.2 External costs and internalization strategies

In the transportation sector, (CE Delft, 2019) classifies external costs into nine categories: accidents, congestion, noise, air pollution, climate change, Well-to-Tank (WTT) emissions, habitat, and infrastructure. Each one of these parcels is related to a different externality caused by transport activity or its infrastructure, even though other classifications can be found in the literature (Merchan & al., 2019) for inland freight transport.

Air pollutant emissions are related to several human health problems but are also extended to material and biodiversity losses. Energy-related air pollutants, PM, and NO_X are largely associated with a higher risk of respiratory and cardiovascular diseases, leading to medical treatment costs, production loss at work, and even death (CE Delft, 2019). Additional issues addressed by air pollutants, such as NO_X, NH_3, and SO_X are crop damage, corrosion on buildings, acidification of soil, precipitation and water, and the eutrophication of ecosystems. Another air pollutant from transportation is the GHG emissions, as already mentioned, associated with climate change consequences.

Applicable to every mode of transport, the Well-To-Tank cost (WTT) takes into consideration up and downstream processes energy production process, but it is not related to direct harmful effects of vehicles' emissions. Different form Tank-to-Wheel (TTW) emissions, WTT comprises the processes of energy generation, processing, and transmission, building of energy plants and other infrastructures lead to emissions of air pollutants and GHG (CE Delft, 2019). Recently added to SA software, the habit damage cost is associated to ecosystem loss, habitat fragmentation, and habitat degradation. Natural habitats of plants and animals can suffer considerable reduction when transport infrastructure requires land surfaces, impacting not just during the building phase but also during the infrastructure lifetime. Large and broad main infrastructures such as motorways and high-speed rail lines also impose population discontinuities by imposing physical barriers.

Only few studies cover the external costs of habitat damage due to transport activities, such as (ECOPLAN; INFRAS, 2014) which presents the external and social effects on the environment in Suisse in 2010, concerning also externalities related to habitat fragmentation and extinction. Results shown that habitat cost could vary between -22% and 27%. External cost in EUR/v-km was obtained from Germany in (UBA, 2019), in which the rates were based on the costs for (virtually) restoring lost biotope or ecosystem areas and, in the case of habitat fragmentation, based on the costs for (virtually) constructing defragmentation structures. In the case of (CE Delft, 2019), the habitat damage cost is calculated based on the infrastructure network length or area, and then, based on the EU28 average values, cost factors for all countries have been calculated, in EUR/v-km. Additional externalities are related to accident, noise and congestion costs, associated to road mode, as further presented in section 3.

The internalization such parcels external costs is responsible for making the transport sector accountable for the full costs of his transport decision. It can be achieved, for instance, through carbon pricing and infrastructure charging. On the literature, several authors have analyzed external cost internalization policies in different ways. (Mostert & Limbourg, 2016) identifies recent work achieved in the field of external costs of road and intermodal freight transport, covering objective, type of externalities, and the type of cost (marginal, average, total) considered in the literature.

The preferable behavior MBM to internalize externalities in the maritime transportation, is to induce operational and technical adaptations through speed reduction in short run and option for alternative fuels and stimulation for the use of abatement technologies in long run (Psaraftis & al, 2021). Among others MBM of the 'Fit for 55' package, the extension of the EU-ETS to maritime transport over the period 2023 to 2025 (EC, 2022) has a strong negative impact on the competitiveness of Ro-Ro and Ro-Pax segments against other modes of transportation (Christodoulou & al, 2021). Additionally, a carbon leakage can also be a side effect of the introduction in the EU EST while container lines in the European Economic Area (EEA) may relocate to ports outside EEA, motivated by reduction on the savings with EU Allowances (Lagouvardou & Psaraftis, 2022).

An increasing share of intermodal transport is obtained by the transport costs and air pollution external costs minimization since rail and IWT modes are less harmful to the environment than road mode. (Mostert, Caris, & Limbourg, 2017). By an economic optimization strategy by incurring road taxes, the road market share compared to the intermodal transport share decreases, but it leads to an underuse of intermodal transport compared to environmental optimization. Some national internalizing systems consist of fairway dues based on environmental ship performance on CO_2, NO_X, SO_X, and PM emissions, going into a different direction of current regulation that aims to penalize maritime transport. The Sweden regulatory system for internalizing external costs in ships computed marginal and infrastructure costs using AIS statistics to compute ship's emission with a bottom-up approach and degree of internalization ranges from 53% to 90% of external costs (Vierth & Merkel, 2022).

In Europe, the degree of internalization of the current road taxation policies concluded that Diesel taxation is not enough for balance externalities from commercial vehicles in most of the 22 EU countries. The best performance taxes over the fuel price are between 40% to 45% of the corrective taxation intended to cover all external costs in Italy, Portugal, and Italy (Santos G. , 2017), highlighting the difficult of establishing a taxation policy without considering HDV refuel in countries where Diesel is cheaper.

To evaluate the environmental competitiveness of SSS and road-only transportation, iso-emissions maps, presenting geographical regions that can be connected by SSS and road with the same level of emissions showed that more environmentally friendly modes is determined by GHG emissions rather than the monetization of its negative impacts (Vallejo-Pintoa & al, 2019)Intermodal routes from Portugal to central Europe regions presented reductions in air pollutant emissions by adopting LNG fuel rather than fueled by VLSFO (equipped with scrubber and Selective Catalytic Reduction), considering vessels with the same capacity, and installed power (Santos & Ramalho, 2021a). Considering economic aspects of power system installation cost and fuel purchase cost, the numerical tool was expanded to compute external costs according to (CE Delft, 2019) for the same geographical scope in (Santos & Ramalho, 2021b) and the best route could be determined by external cost internalization for a set of destination connected by different routes, demonstrating the importance of more intense externalities monetarization to reduce transport externalities.

3 METHODOLOGY

3.1 Air pollutant emission method

Air pollution emission are computed in a link basis, which means that the mass of pollutant is computed to a specific link k, part of a path j connecting a specific pair O/D i. Each pair O/D is connected by many j different transport chains, and the evaluation of the total emission is given by the sum of each emission in all links.

The methodology for estimating GHG and air pollution emissions using emission factors is divided into fuel-based method (directly relate the mass of pollutant emitted to the mass of fuel consumed [g/g]) or energy-based methods (relate the mass of pollutant to the energy required [g/kWh]). The mass of PM and NO_X emissions (generically pollutant p) is computed directly from the fuel-based emission factor $EF_{e,p}$, in g/kWh, multiplied by the power demand, in kW, and time on the link, in hours, given by the link distance L_{ijk} divided by link speed V_{ijk}:

$$E_{ijk,p} = EF_{e,p} \cdot P_D \cdot \frac{L_{ijk}}{V_{ijk}} \tag{1}$$

and, for GHG and SO_X, emissions are computed using the specific fuel consumption SCF_{ij}, in g/kWh, and the fuel-based emission factor:

$$E_{ijk,p} = EF_{f,p} \cdot SCF_{ij} \cdot P_D \cdot \frac{L_{ijk}}{V_{ijk}} \tag{2}$$

Therefore, emission estimations are based on the estimate the power demand and the fuel consumption, which depends on the vehicle specifications in each mode of transport.

For the links identified by road transport, the power is approximated by the power required to overcome the total resistance force $F_{T,ijk}$, in kN, at certain speed V_{ijk}, in km/h, considering a transmission efficiency η_t:

$$P_{D,ijk} = \frac{F_{T,ijk}}{\eta_t} \cdot \frac{V_{ijk}}{3.6} \tag{3}$$

Under assumptions of plane roads and constant speed in the link, the resistance the resistance force is composed by the air drag and rolling resistance forces:

$$F_{T,ijk} = \frac{1}{2} \cdot \rho_{air} \cdot C_d \cdot A_f \cdot \left(\frac{V_{ijk}}{3.6}\right)^2 + C_{rr} \cdot M_{ij} \cdot g \tag{4}$$

in which ρ_{air} is the air density (in kg/m^3); g is the acceleration of gravity (in m^2/s); C_d is the drag coefficient; A_f is the frontal area (in m^2); C_{rr} is rolling resistance coefficient; and M_{ij} is the truck gross weight (in kg), including cargo and tare weights.

HDV technical parameters needed were extracted from (Gao & al, 2015). For accounting with congestion, speed reduction coefficients were applied in Equations (3) and (4). The congestion condition in the road is determined by the ratio between road volume and capacity and based on Traffic Flow Theory, the road that the speed reduction coefficient is determined (CE Delft, 2019).

The emission factors for NO_X, PM and SO_X are given by the automotive Diesel fuel quality in Europe, specified by the EN590 standards. The standard EURO considered is the stage V with a maximum permissible sulphur content of 10 ppm after 2011 for road and non-road mobile machinery (EU, 2009). For the $CO_{2\text{-eq}}$ emission factor is the sum of the most relevant pollutants responsible for global warming (CO_2, CH_4, N_2O), weighted by their global warming potential, resulting in 3.181 g/g for Diesel engines and 3.104 g/g for LNG engines.

The estimation of the power demand in Diesel and electric traction locomotives considers some specifications of the railway corridor, such as the train length (long or extra-long) and cargo unit load (light, medium and heavy weight transport). By these parameters, the gross-tonnage weight and the energy consumption are obtained from empirical data in (CE Delft, 2021). Then, the locomotive power demand $P_{D,ijk}$, in kW, is given by:

$$P_{D,ijk} = \frac{EC_{ij}}{3.6} \cdot GTW \cdot V_{ijk} \tag{5}$$

in which the energy consumption is EC_{ij}, in MJ/tkm, the train gross-tonnage weight is GTW, in ton.

The fuel consumption of a typical Diesel engine was assumed 219 kg/h for estimating the fuel-based emissions. A conventional sulfur content of 10 ppm is adopted according to the same Diesel fuel quality established to HDV and energy-emission factors were extracted from Directive 2010/26/EU and Regulation 2016/1628, regarding non-road mobile machinery standards Stages III and V, respectively.

Emissions abatement technologies available for Diesel railway engines can be adopted on the software. The use of Diesel Particulate Filter (DPF) provides significant reduction in particulate matter emission factor and Exhaust Gas Recirculation (EGR) represents cuts on nitrous oxides (EMEP/EEA, 2019). Whether the Diesel locomotive comprises with the Stage V standards for PM emissions, it is already assumed that the trains is equipped with DPF technology (EPA, 2018). For railways, it was considered that 95% of calculated PM_{10} is $PM_{2.5}$.

In maritime transport, several engines demand power in different loads, depending on the ship's operational profile. The cruise, maneuvering or port profiles are determined by the main engine load (IMO, 2020). The effective power $P_{EF,ijk}$, kW, to the ship overcome the resistance force at speed V_{ijk}, in a draft D'_{ij}, in m, lower than the design draft D_{ij}, in m, is given by an adaptation of the Admiralty Formula:

$$P_{EF,ijk} = \frac{PME_{ij} \cdot \left(\frac{V_{ijk}}{V_{ij} \cdot 1.852}\right)^{3} \cdot \left(\frac{D'_{ij}}{D_{ij}}\right)^{0.66}}{\eta_w \cdot \eta_f} \qquad (6)$$

in which PME_{ij} is the installed main engine power and V_{ij} is the ship design speed, in knots, at 100% of maximum continuous rating (MCR) with clean hull and calm sea.

Some limitation of the formulation below can be the simplification of a constant fouling and weather efficiency and the power of 1/3 in displacement relation (draft ratio) may be lower in low steam (Berthelsen & Nielsenac, 2021).

The variation of cargo onboard significantly impacts the fuel consumption and emission. For accounting with this effect, a draft variation is introduced according to the cargo utilization capacity. By assuming a constant water plane and parallel sides, the definition of water plane area coefficient c_w and water displacement lead to the following equation for the reduced draft D'_{ij}, under a lower cargo utilization factor Ut_{ij}:

$$D'_{ij} = D_{ij} - \frac{DWT_{ij} - W_{FEU} \cdot Cap_{ij} \cdot Ut_{ij}}{c_w \cdot L_{PP_{ij}} \cdot B_{ij} \cdot \gamma} \qquad (7)$$

in which DWT_{ij} is the vessel's design deadweight (in tons), W_{FEU} cargo unit Cap_{ij} is the vessel's capacity (in FEUs), ship length between perpendiculars $L_{PP_{ij}}$ and moulded breadth B_{ij}.

In the cruise profile (main engine load above 25%), the main engine fuel consumption may be increased using shaft generators, a Power Take-Off system (PTO). The load of this equipment is assumed constant and the main engine fuel consumption at sea, in kW, is $FC^{sea}_{ME,ij}$:

$$FC^{sea}_{ME,ij} = \sum_{k=1}^{K} SFC_{ME,ijk} \cdot (P_{EF,ijk} + L^{sea}_{PTO} \cdot PTO_{ij}) \cdot \frac{L_{ijk}}{V_{ijk}} \qquad (8)$$

in which the specific fuel consumption of the main engine is $SFC_{ME,ijk}$, in g/kWh, and the shaft generators power is PTO_{ij}, in kW, with a load utilization factor of L^{sea}_{PTO}.

The specific fuel consumption for the main engine is given by a parabolic function on the main engine load, accounting with PTO, in which the optimum fuel-consumption point corresponds to the basic specific fuel consumption, at approximately 80% load. This parameter is given by from engine manufacturers, depending on the propulsion system and fuel type used.

$$SFC_{ME,ijk} = SFC_{base} \cdot (0.455 \cdot {L^{sea}_{ME,ijk}}^{2} - 0.710 \cdot L^{sea}_{ME,ijk} + 1.280) \qquad (9)$$

An extra fuel consumption is carried out by auxiliary generators, assumed to operate in a constant load, which varies with the ship's operational profile, and a constant specific fuel consumption. In the maneuvering profile, the fuel consumption is only carried out by the shaft generator, given by Equation (7) but it is assumed a different generator load L^{mano}_{PTO}, and excluding the effective power. In the port profile, the fuel consumption is simply given by the time spent moored and the

$$FC^{port}_{AE,ij} = SFC_{AE} \cdot L^{port}_{AE} \cdot PAE_{ij} \cdot T_{P,ij} \qquad (10)$$

A lower combustion efficiency is noticed when the main engine operated in low load and PM and NO_X emission factors increase. To represent such effect, magnifying coefficients are introduced when main engine loading condition is below 10% and 2% MCR of installed main engine power (IMO, 2020). As typically assumed on the literature, the total emission is obtained by computing PM_{10} and assuming that 92% of the calculated value is $PM_{2.5}$ (IMO, 2020). The computed PM_{10} emission factor is a function of the fuel's sulfur content. For computing NO_X emissions, the Tier emission limits are used as emission factors, depending also on the engine rated speed. In this study, medium speed engines are considered to have a rated speed of 500 rpm for applying the emission factor formulation which depends on the rating speed.

The same power and fuel consumption estimation methodology is applied to inland waterway transport (IWT), but some simplifications are assumed: power demand for propelling a self-propelled barge or pusher in a convoy is given by the original Admiralty formula, disregarding draught variation; fuel consumption was assumed to be 5% of the fuel consumption for the main engine (high speed generators with small installed power usually fueled by MDO/MGO).

3.2 External cost estimation method

For emissions external costs, the methodology for computing the average Air Pollution cost $C_{AirPol,ij}$, in each path j part of the pair origin destination i, is obtained by equation below, multiplying the pollutant emissions $E_{ijk,SO_{2,}}$, E_{ijk,NO_X}, and $E_{ijk,PM_,}$ (in grams) by its respective costs c_{tonSO_2}, c_{tonNO_X} and c_{tonPM} (in EUR/ton of pollutant), respectively.

$$C_{AP,ijk} = \left(c_{tonSO_2} \cdot E_{ijk,SO_{2,}} + c_{tonNO_X} \cdot E_{ijk,NO_{X,}} + c_{tonPM} \cdot E_{ijk,PM_,}\right) \cdot 10^{-6} \qquad (11)$$

In the same way, the Climate Change cost $C_{CC,ij}$ is given by the multiplication of the equivalent $CO_{2\text{-eq}}$ emissions $E_{ijk,CO_{2-eq}}$ by the carbon price c_{tonCO_2}:

$$C_{CC,ijk} = c_{tonCO_2} \cdot E_{ijk,CO_{2-eq}} \cdot 10^{-6} \qquad (12)$$

Externalities related to other transport externalities Accident, Noise, Congestion, Well-To-Tank (WTT) and Infrastructure costs, are simply computed by multiplying the distance travelled L_{ijk} in the link by its respective marginal cost, in cent-EUR/vehicle-km and the transfer value is K_r:

$$C_{ext,ij} = K_r \cdot c_{ext} \cdot L_{ijk} \cdot 10^{-2} \qquad (15)$$

4 NUMERICAL TOOL AND VALIDATION

The numerical model previously presented was implemented in a software named Sustainability Analysis (SA). The workflow structure follows a log file to internally identify input and output file's names for further opening and reading of each data. The input data provide basic information about the transport network (relates pairs O/D to nodes and link sequences, vehicle technical specification, path activity), link characteristics (link distance, link country, classification area, speed, and transport mode), vehicle's technical characteristics, external cost coefficients, transfer values, and emission factors. The output files present to each pair O/D, emissions, and external costs per transport mode and total per possible set of paths, per country, results in list format for better manipulation on Excel. SA presents some modifications from the 2019 version, i.e., differentiation of number of paths per pair O/D, introduction of input parameters for vehicle definition, integration with internal cost software output, new output files (including post-processing data), and inclusion of PTO systems.

The results validation was carried out by implementing the numerical methodology in a worksheet in MS Excel, evaluating air pollutant emissions and external costs parcels per unit of cargo different paths for one pair O/D contained in the database. Three paths connecting Porto, Portugal, to Stuttgart, Germany, were considered: road-only transport composed of 59 links, intermodal transport chain comprising road and rail mode and composed of 70 links, intermodal transport chain comprising road, inland waterway, and maritime modes and composed of 47 links, considering vessel fueled with VLSFO and a combination of WS and EGR abatement technologies inside SECA, and vessel propelled by a Tier 3 engine LNG-fueled. The absolute difference in every path analyzes in different transport modes was up to 6E-2 for emissions and 4E-2 for external cots, with higher precision in land-based modes. These errors were associated with number rounding in the output file.

Online emission calculators were tested to validate the emission model present some assumptions that do not reflect the reality in its complexity. For instance, in maritime transport, ports distances are uncertain, the ship type, cargo capacity and installed power are not inputs on the model. Regarding road mode, more accurate results were obtained with 10% variation on average compared to the software GHG emissions output.

5 CASE STUDY

The NUTS classification is a hierarchical system aiming to split up the EU and UK territories for socio-economic analysis and its second degree (NUTS2) of specification represents basic regions of countries covered in this study. The origin of transport chains is Porto, connected to 188 NUTS2 destination in Spain, France, Germany, Italy, Denmark, Switzerland, Czech Republic, Netherlands, Belgium, Luxemburg, Austria, and the United Kingdom, countries responsible for handling, on average, 20 million tons of goods per year, equivalent to 20% of the Portuguese exportations by sea (APP, 2022; BPstat, 2022). Appendix 1 presents the intermodal chains connecting Porto to different destinations, including the only-road transport and 25 intermodal chains through different terminals and vessels (RoRo or container ship). Two different routes possibilities are defined in this study, intermodal route covering the existing routes (Scenario 1) and new intermodal chains through Mediterranean ports, railway corridors and Rhine-Danube inland waterways (Scenario 2). Appendix 2 presents each transport chain related to countries served and which scenario the chain is included.

Emissions estimations and external costs per unit of cargo transported depends on the cargo utilization capacity, a difficult parameter to be estimated. For this reason, scenarios were divided in ships and trains at 50% and 80% cargo. To evaluate European rail network, in which 60% of railway lines are electrified and 80% of traffic is running on these lines (EC, 2017), an additional division of scenarios was proposed to compute electric and Diesel traction. Table 1 summarize the scenarios defined considering variables mentioned.

Table 1 – Scenarios description

Scenario	Cargo utilization	Train type
1.1	50%	-
1.2	80%	-
2.1	50%	Diesel
2.2	80%	Diesel
2.3	50%	Electrical
2.4	80%	Electrical

The technical specifications of vehicles in the study case are associated to the average HDV and inland vessel applied in the transport lines serving the geographical area mentioned. For road transport mode, a Class 8 long-haul truck was considered representative of trucks used in long distances road freight transport in Europe, with 30 tons laden weight (Eurostat, 2022) and respecting the Directive 96/53EC (ACEA, 2015). The inland navigation is carried out by the Large Rhine Vessel class, a large multipurpose vessel that mainly operates in the Rhine River and it is equipped with a Diesel Particulate Filter (DPF) and scrubber in accordance with EC directives (Interreg, 2018; Interreg, 2017).

Table 2 – Truck and barge technical specifications

Truck	Barge
- Travel time: Day - Container weight: 30 ton/FEU - Truck type: Articulated - Truck weight: 40 ton - Fuel type: Diesel - Euro emission class: 5 - Specific fuel consumption: 215 g/kWh - Engine power: 365 kW	- Directive stage: II - Fuel quality: EN590 - Emission abatement technology: DPF+SCR - Rating speed: medium speed - Cargo capacity: 1,500 ton - Barge capacity: 50 FEUs - Cargo utilization: 100% - Installed Power: 737 kW - Cruise Speed: 10 knots

Table 3 summarizes the average length, speed and cargo capacity of trains, with data extracted from Rhine-Alpine, Atlantic, and Scandinavian-Mediterranean railway corridors (RFC Rhine-Alpine, 2021; Atlantic Corridor, 2020; TRT, 2019; FFE; RC, 2020; EC, 2020).

Table 3 – Rail freight corridors (RFC) characteristics

Path	From	To	RFC	Speed [km/h]	Length [m]
4	Rotterdam	Oberhausen	Rhine-Alpine	71	530
6	Leixões	Entroncamento	Atlantic	50	400
7	Leixões	Cacia	Atlantic	50	400
8	Rotterdam	Mannheim	Rhine-Alpine	71	530
9	Le Havre	Mannheim	Atlantic	63	700
12	Hamburg	Wurzburg	Scandinavian-Mediterranean	-	600

Freight container transportation by sea is carried out by RoRo and container ships from port of Leixões to other European port. A typical vessel, operating in a line to port of Rotterdam, was used for characterizing every other path travelled by the same ship type. Container vessels research took place to identify container ships applied in actual lines from Portugal. Among 12 regular container lines, operated by 7 different shipping companies, vessel name and IMO number of container ships in operation were found on the operator's websites and ship's particulars were obtained from *Scheepvaartwest* website (Table 4).

Table 4 – RoRo and Container ship technical specifications

Vessel	1	2	3	4	5	6	7
LPP [m]	195	158	131	166	127	125	142
B [m]	26.2	27.2	22.8	27.4	19.4	22.5	23.4
D [m]	7.4	13.6	8.7	10.9	7.36	8.71	8
DWT [t]	13,625	15,952	12,558	23,286	8,496	11,252	13,172
Cap [FEU]	217	800	462	848	353	402	518
Tier	2	2	2	2	2	2	2
Rete speed	MS	SS	MS	SS	MS	MS	MS
PME [kW]	5,905	12,640	9,600	18,820	7,195	8,400	9,000
PAE [kW]	2,540	2,400	1,500	3,540	860	2,036	1,650
PTO [kW]	3,750	3,400	1,700	900	1,315	2,238	2,500
V_{ij} [kt]	15	20	18.3	20.5	17.9	18.5	18.5

The power loading of Vessel 1 was obtained from the RoRo operator in real operational conditions, considering information of shaft generator. For the container ship, typical values found in the literature were applied. Table 5 summarize the container ship and RoRo loading conditions used as software input.

Table 5 – Power loading condition for container ships and RoRo

	Container ship loading			RoRo power loading		
Machinery	Cruise	Port	Maneuver	Cruise	Port	Maneuver
ME	100%	0%	0%	100%	0%	0%
AE	30%	50%	40%	0%	7%	84%
PTO	0%	0%	0%	60%	0%	100%

6 NUMERICAL RESULTS

Air pollution and GHG emissions were computed using the SA software in road-only and intermodal chains connecting Porto to 188 NUTS2 region in Europe. The preferable chain to serve each NUTS is then chosen based on 3 different criteria – the least external costs, the least internal cost, and the least full total transport costs. The route preference by the introduction of intermodal chains in the Portuguese trade under cargo capacity uncertainties and considering electric and Diesel railway traction, was assessed by a series of maps (Appendix 3), presenting the competitiveness of each transport mode to ensure environmental or economic performance.

6.1 Route preference regarding external cost

Considering external cost criteria at 50% cargo capacity, the current scope of intermodal routes (Scenario 1.1) showed that only-road transportation is competitive in 40% of the cover area on the map. Especially in Spain and western France, the geographic proximity from the North of Portugal implied in further distances from ports or rail terminal considered and consequently longer road distances than direct road transport. Intermodal transport chains to destinations in Western and Central Europe presented, on average, 44% and 40% reductions in total externalities (compared to road-only transport) by adopting port of Rotterdam and Hamburg in eastern France, Germany, Belgium, Luxemburg, and the Netherlands.

In Scenario 2.1, the introduction of new intermodal routes was responsible for reducing to 28% de total area of road preference compared to 40% in the previous scenario, considering the same cargo utilization. Regions in central Europe are served by port of Le Havre rather than road mode or port of Rotterdam due to the economy of scale provided by a container ship with high cargo capacity, especially in WTT cost. The port of Marseille provides externalities savings to southern France, and in Italy, the port of Salerno serves the Southern Italy, previously reached by a road path from the port of Genoa in Scenario 1.1.

Now, considering vessels and trains at 80% capacity, the area of influence of road-only transportation has increased in Scenario 1.2 to 31% compared to 28% in Scenario 2.1, but improvement occurs when compared to Scenario 1.1, situation using the same transport chain scope at lower cargo utilization. For instance, the port of Valencia, that presented a worse external cost than road mode, became competitive at 80% capacity, with 32% reduction in the external cost at 50% capacity. Switzerland, previously served by only-road mode is now served by the port of Genoa. The economy of scale is even higher considering Scenario 2.2, in which the full scope of intermodal routes and 80% capacity are responsible for external cost savings in maritime mode.

Regarding electric traction, at 50% capacity, Scenario 2.3 do not show a different preference configuration compared to Diesel trains scenario. This happened because electric saving in air pollution and GHG gases did not compensate for savings in chains that combine different transport modes. However, comparing the same route with Diesel traction, total externalities were in fact reduced by 16% in the region of activity of railway corridor from Genoa, even though WTT cost increased 7% in electric traction. For the Atlantic corridor from Cacia and Entroncamento terminals, externalities were reduced even more (35% lower than Diesel). In Scenario 3.4, the preference to railway mode is noticed when considered 80% cargo utilization of electric trains, extending the influence of railway corridor from Genoa to Basel to great part of Switzerland.

Table 6 establish the effectiveness of different strategies for reducing the environmental and human health impacts of transportation – intermodal chains, increasing capacity and electric traction. The highest decrease of total external cost is related to an increased cargo utilization factor, motivating a preference to maritime mode. Regarding the full scope of intermodal transport chains, the externalities reductions were significant in Congestion, Accident and Noise, but WTT, Climate Change, and Habitat costs have increased due to lower external cost in certain countries. For an increasing 80% cargo capacity, the transport chain configuration was favorable to electric rail transport chains, but it was restricted by the air pollution cost increment related to the emissions in the maritime path from Leixões to Genoa, which emitted more polluters than the maritime path to Le Havre and degrades the complete route that makes use of railway to Basel.

Table 6 - Percentual savings in total external cost

Variable	External cost
Intermodal chains at 50% capacity	-15%
Intermodal chains at 80% capacity	-20%
Increase capacity in current chains	-22%
Increase capacity in new chains	-22%
Use of electric train at 80% capacity	-10%

6.2 Route preference regarding the total transport cost

Regarding the chain preference based on the least total transport cost, fully internalizing external costs, new maps are shown in

Figure 3 per scenario simulated. Firstly, considering only internal costs, road transport is associated to lower transport costs, but it is associated with higher human health and environment impacts.

Generally, Table 7 summarize the number of NUTS regions in which the transport chain changed from the least internal cost map to the external cost internalization map, highlighting the mode of transport and intermodal terminal involved in this change.

Table 7 – Number of route preference shifts after external costs internalization

Scenario	Only-road to container	Container/ RoRo to container	Rail to container	#NUTS	%NUTS
1.1	43	2	0	45	24%
1.2	54	2	0	56	30%
2.1	41	5	2	48	26%
2.2	55	5	2	62	33%
2.3	42	5	2	49	26%
2.4	56	5	1	62	33%

It is possible to conclude that more than 85% of route preference shifts in all scenarios tested concern the adoption of water-borne transportation instead of only-road mode. Even though WTT costs have strong influence in ship’s total external cost, some externalities related to road mode are considered negligible in ships, such as Accident, Noise and Congestion, penalizing chains with long road distances. Furthermore, other shifts are associated with preference to other port, caused by specific vehicle characteristics associated with each route - such as the vessel’s capacity and installed power, train’s length –, but also terminal-specific costs, responsible for lower internal costs.

Notably, considering the full scope of routes (Scenario 2) was responsible for the highest number of preference changes due to the environmental advantages presented by intermodal routes, most of them still is not used. A broader range of route possibilities, comprising intermodal paths in different ports of call, presented a reduction in external costs and consequent increase in competitiveness of other modes of transportation. Summed to a higher cargo utilization factor, the number of modal shifts goes up to 33% of all regions considered

7 CONCLUSIONS

The environmental and human health impacts of a complex transportation network from Porto to major European commercial partners of Portugal were successfully assessed considering economic and environmental aspects. The competitiveness of the new scope of transport chains through port on the West Mediterranean, the Atlantic railway corridor and new port of calls in North Sea was evaluated regarding internal, external, and total transportation costs. Some conclusions can be obtained about preferable transport chains regarding the least external cost:

- SSS services from Portugal had at least 40% lower external costs by the adoption of transport chains through Western European ports, such as ports of Hamburg and Rotterdam. The percentual reduction is even higher on regions close to the port areas and considering vessels.
- Increasing competitiveness of the full scope of intermodal transport chains, due to about 15% lower external costs, has allowed 7% higher number of NUTS2 regions served preferably by SSS services (at 50% cargo capacity utilization).
- WTT emissions has a major impact on maritime services, on average, comprises 35% of external cost, considering 50% cargo utilization, and 33%, considering 80% utilization. The maritime transport environmental performance is, then, determined by WTT cost.
- Paths through western European ports decreased by at least 40% the total external cost, with a higher impact on regions close to the port areas.
- Electric trains reduced external costs in 16% but did not affect chain preference at low cargo utilization factors. The railway service was deteriorated by the previous maritime path associated to the intermodal transport chain because of the low cargo capacity of RoRo vessels.

Regarding the effects of the full internalization of external cost in the transportation cost, the analysis of the maps shows:

- Compared to preferred chains regarding the least internal cost, transport chain preferences changed from road-only transport mode to SSS services in 22% of NUTS 2, considering 50% cargo capacity utilization and Diesel locomotives, and 30% of NUTS 2, at 80% cargo capacity utilization and electric locomotives.
- Map preferences regarding the total transport cost resulted close similarity to the preference regarding only the least internal cost related because external costs comprise only 29% of total transport cost.
- The balance between internal and external costs is noticed in Switzerland and Germany when considering electric traction trains, justifying its chain preference.
- Accounting only for internal transport costs, the road-only mode is the most competitive route due to fewer costs in comparison to chains involving the use of intermodal terminals. In this context, intermodal chains are preferable only in regions with good connections between different transport modes, such as in the Netherlands and northern Germany.

Future works can focus on WTW emission calculations, offering reliable numerical estimations of WTW emissions; appliance of LCA in transport activity; measurement of effectiveness of new regulations for meeting the EU Green Deal goals; carbon savings by varying carbon prices, introduced by ETS, and new fuel regulations; preference route by the least air pollutants and GHG emission separately to evaluate carbon leakage; evaluation of degree of internalization of European MBM by taxations over environmental performance and human health in different modes of transportation.

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APPENDIX 1 – PATHS DESCRIPTION

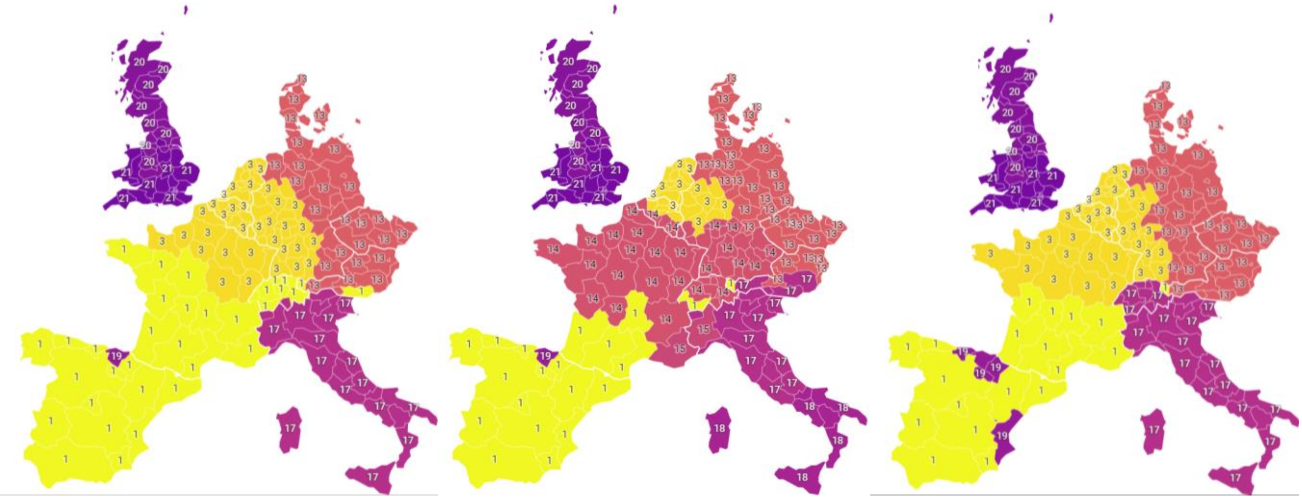
Path	Modes	Terminals	Vehicles
1	Road	-	Truck
2	SSS Road	Rotterdam -	Container ship Truck
3	SSS Road	Rotterdam -	RoRo ship Truck
4	SSS Rail Road	Rotterdam Oberheim -	RoRo ship Train Truck
5	SSS IWT Road	Rotterdam Duisburg -	RoRo ship Barge Truck
6	Rail Road	Entroncamento -	Train Truck
7	Rail Road	Cacia -	Train Truck
8	SSS Rail Road	Rotterdam Mannheim -	RoRo ship Train Truck
9	SSS Rail Road	Le Havre Mannheim -	RoRo ship Train Truck
10	SSS Road	Le Havre -	RoRo ship Truck
11	SSS Road	Hamburg -	RoRo ship Truck
12	SSS Rail Road	Hamburg Wurzburg -	RoRo ship Train Truck
13	SSS Road	Hamburg -	Container ship Truck
14	SSS Road	Le Havre -	Container ship Truck
15	SSS Road	Marseille -	Container ship Truck
16	SSS Road	Valencia-Naples -	RoRo ship Truck
17	SSS Road	Setubal-Genoa -	Container ship Truck
18	SSS Road	Setubal-Genoa-Salerno -	Container ship Truck
19	SSS Road	Bilbao or Valencia -	Container ship Truck
20	SSS Road	Liverpool -	Container ship Truck
21	SSS Road	Tilbury -	Container ship Truck
22	SSS Road	Bristol -	RoRo ship Truck
23	SSS Road	Livorno -	RoRo ship Truck
24	SSS Rail Road	Hamburg Basel -	Container ship Train Truck
25	SSS Rail Road	Genoa Basel -	Container ship Train Truck
26	SSS IWT Road	Rotterdam Basel -	RoRo ship Barge Truck

APPENDIX 2 - SCOPE OF INTERMODAL ROUTES IN SCENARIOS 1 AND 2

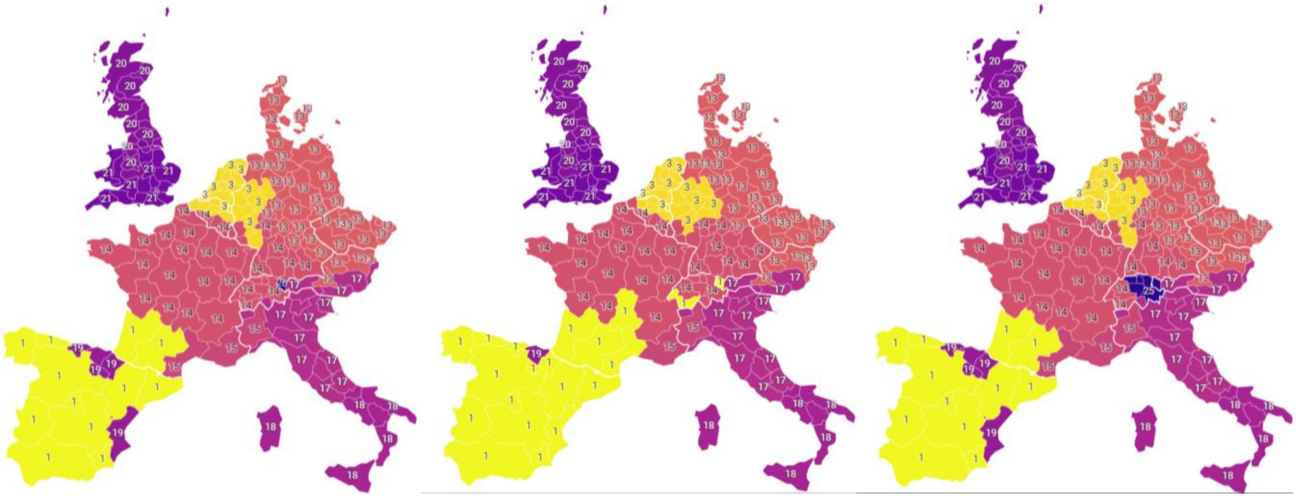
Path	Description	ES	FR	IT	LU	BE	NL	DE	CH	AT	CZ	DK	UK
1	Road	x*	x*	x*	x*	x*	x*	x*	x*	x*	x*	x*	x*
2	RoRo (Rotterdam) + Road		x		x	x	x	x			x		
3	Containership (Rotterdam) + Road		x*		x*	x*	x*	x*	x*	x*	x*	x*	
4	RoRo (Rotterdam) + Rail (Oberheim) + Road		x		x	x	x	x					
5	RoRo (Rotterdam) + IWT (Duisburg) + Road		x		x	x	x	x					
6	Rail (Entroncamento) + Road		x		x	x	x	x					
7	Rail (Cacia) + Road		x		x	x	x	x	x	x	x		
8	RoRo (Rotterdam) + Rail (Mannhein) + Road		x		x	x	x	x					
9	RoRo (LeHavre) + Rail (Mannhein) + Road		x		x	x	x	x					
10	RoRo (LeHavre) + Road		x		x	x	x	x					
11	RoRo (Hamburg) + Road		x		x	x	x	x				x	
12	RoRo (Hamburg) + Rail (Wurzburg) + Road		x		x	x	x	x					
13	Containership (Hamburg) + Road		x*		x*	x*	x*	x*		x*	x*	x*	
14	Containership (LeHavre) + Road		x		x	x	x	x	x				
15	Containership (Marseille) + Road		x	x					x				
16	RoRo (Valencia-Naples) + Road			x									
17	Containership (Setubal-Genova) + Road			x*					x*	x			
18	Containership (Setubal-Genova-Salerno) + Road			x									
19	Containership (Bilbao/Valencia) + Road	x*											
20	Containership (Liverpool) + Road												x*
21	Containership (Tilbury) + Road												x*
22	RoRo (Bristol) + Road												x
23	RoRo (Livorno) + Road			x					x				
24	Containership (Genova) + Rail (Basel1) + Road		x		x	x		x	x	x			
25	Containership (Genova) + Rail (Basel2) + Road		x		x	x		x	x	x			
26	RoRo (Rotterdam) + IWT (Basel) + Road		x		x	x		x	x	x			

* Transport chains considered in Scenario 1.

APPENDIX 3 – RESULTS OF PREFERANCE MAP

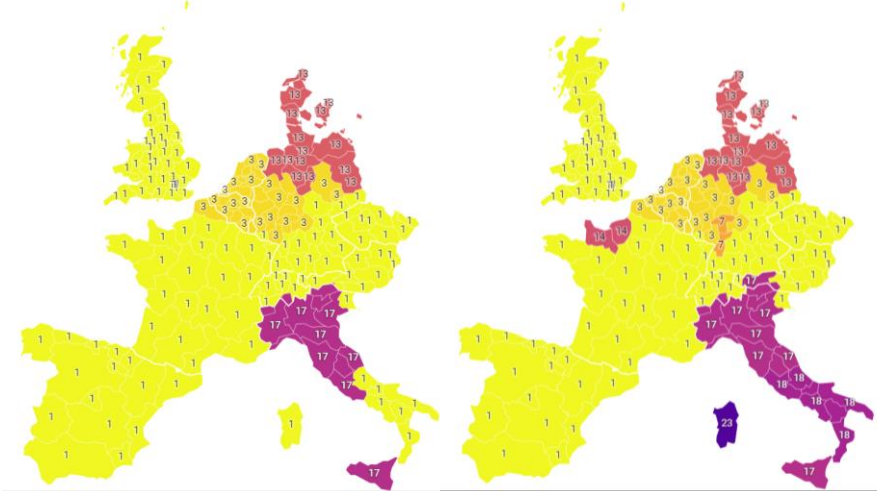


(a) Scenario 1.1 (b) Scenario 2.1 (c) Scenario 1.2



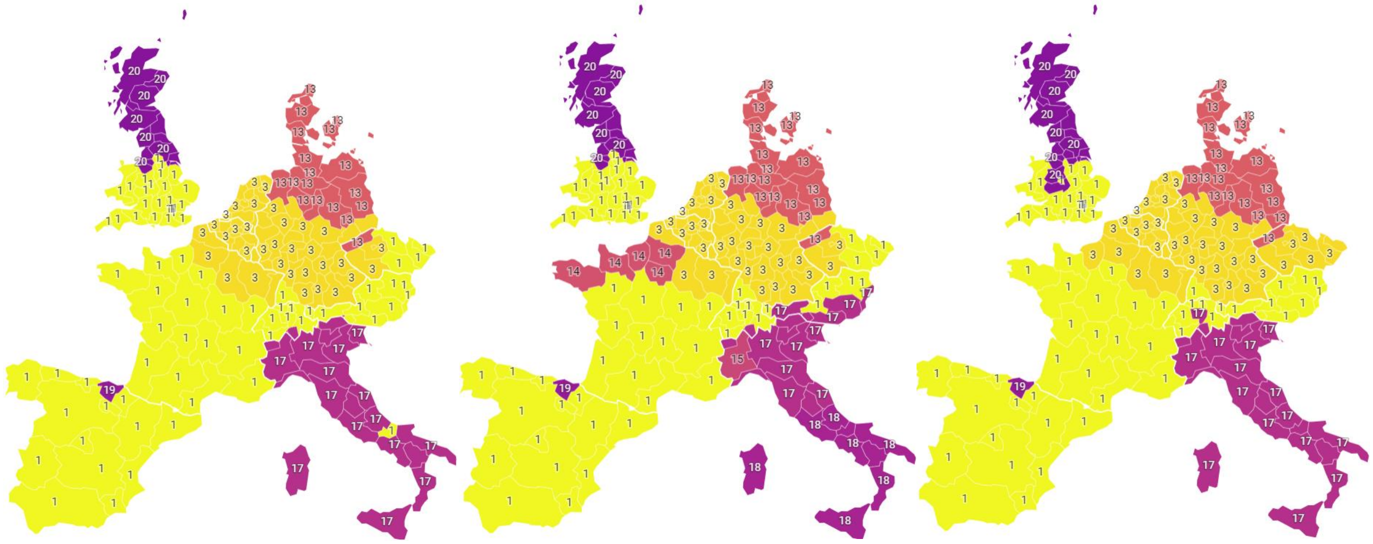
(d) Scenario 2.2 (e) Scenario 2.3 (f) Scenario 2.4

Figure 1 – Route preference criteria with lowest external cost criteria

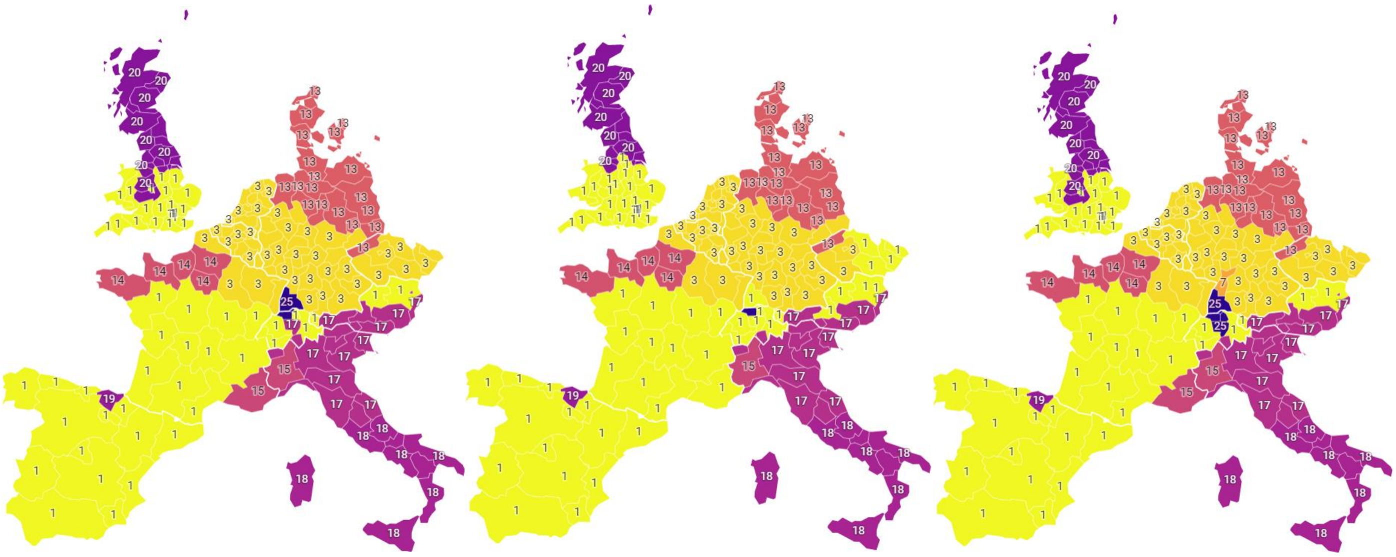


(a) Scenario 1 (b) Scenario 2

Figure 2 – Route preference criteria with lowest internal cost criteria



(a) Scenario 1.1 (b) Scenario 2.1 (c) Scenario 1 .2



(d) Scenario 2.2 (e) Scenario 2.3 (f) S cenario 2.4

Figure 3 – Route preference criteria with total transport cost criteria