Choice of propulsion plants for container vessels operating under SSS conditions in the E.U.: an assessment focused on the environmental impact on the intermodal chains

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Abstract

The unbalanced evolution of the environmental normative in the European Union for the different transport modes has led to a broader debate about whether Short Sea Shipping (SSS) is still a green transport mode. This discussion is especially pertinent because there is not a technological alternative indisputably identified as the most adequate one to meet the emission requirements in the Emission Control Areas (ECA) without penalizing the competitiveness of SSS. The objective of this paper is to assess the performance of intermodal chains versus trucking in terms of costs, times, and externalities when the selected fleet for SSS is made up of optimal container vessels operating with different propulsion plants and fuels in compliance with ECA requirements. This is, Tier III four-stroke diesel engine with MGO, a Tier III four-stroke diesel engine Tier-III with scrubber and HFO, and a four-stroke dual engine operating with LNG. To this aim, a mathematical model which is able to provide optimized technical and operative features of the vessels, is modified and solved for an intermodal chain between Spain and France through the Atlantic coast. This study shows that dual LNG engines prove to be not only the most sustainable solution but also the most suitable in terms of costs, as long as the difference

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in price between LNG and petroleum fuels is equal to the base case or within a modification range of 20%. This study also highlights that, due to the limited range of SSS vessels, the loss of the cargo capacity in holds by the gas tanks arrangement was not significant.

Keywords:

Short Sea Shipping, Externalities, Environmental Costs, Evolutionary Algorithms

1. Introduction

The concept of Motorway of the Sea (MoS) was collected in the White Paper on European Transport Policy for 2001 as a group of intermodal services and ports where Short Sea Shipping (SSS) is able to offer 'door-to-door' transport services [1-3]. Since then, the intermodality through MoS has traditionally been regarded as the most sustainable solution for the congestion problems of European roads. Nonetheless, the subject has been under discussion in recent years. The measurements of several environmental pollutants (beyond the CO_2 emissions) and the technical and operative features of the most suitable vessels which cover this type of maritime traffic (small and fast vessels; [4]) have shown that the green label for intermodal chains through the MoS is clearly under discussion [5-7]. This issue is particularly significant in the context of criticisms about the unbalanced treatment of transport modes by the European Union (EU) [8,9].
In fact, the evolution of normative restrictions concerning pollutant emissions from the maritime transport in the EU has been significantly slower and laxer than those from road transport [9].

The standards Euro I to Euro VI have guided the technological evolution of trucks in the EU since the 1990s (Directive 91/542/EEC, amending Directive 88/ 77/EEC). These regulations have tackled the sequential reductions in environmental pollutants from road transport. Thus, the demand to apply Euro VI technology, which has been compulsory in the EU since January 2014 (Regulation EC N 595/2009 as amended by Regulation 582/2011, for Heavy Duty Vehicles –HDV- category N3), has involved a reduction of 50% in particle pollutants and a reduction of 77% in NOx emissions in relation to Euro V standards (Regulation 582/2011). Consequently, the technological development of these trucks has followed the demands imposed by European Regulations since the 1990s.

However, this has not occurred for EU maritime transport where environmental regulations have mainly relied on the International Maritime Organization (IMO) normative, specifically: The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Annex VI (Regulations for the Prevention of Air Pollution from Ships) which restricts SO_2 and NO_x emissions.

Despite the fact that this regulation permits special protection for certain EU zones (the Baltic Sea, the North Sea, and the English Channel) - classified as the 'Sulphur Emission Control Area' (SECA) which implies that the sulphur content of fuels used in these zones from January 2015 must not exceed 0.1% on a mass basis - this regulation is less demanding and has had a slower evolution than the land normative. As a consequence, even when the vessels comply with the latest environmental requirements, the disadvantage in terms of NO_x and SO_2 emissions for the intermodal chain regarding trucking is notable [5,6]. Europe has attempted to balance the situation by means of the European Parliament Directive (EU) 2016/802 that introduced, as a target, the drastic reduction in sulphur emissions permitted across all European territorial seas and Exclusive Economic Zones from 2020 (in line with the IMO requirements).

In parallel, the conclusions of the European Environmental Agency's (EEA) (Technical Report No. 4/2013) led to a communication from the European Commission to the European Parliament COM (2013) 479 which attempted to force the convergence of CO_2 emissions from maritime transport with the CO_2 emissions aims declared in the White Paper on Transport (2011). Specifically, the COM (2013) 479 suggested a 'step' strategy. The first step, introduced by the European Parliament's Regulation (EU)2015/717, demands the installation of Monitoring, Reporting, and Verification (MRV) systems for CO_2 emissions on vessels (with compulsory reports from 2018).

Aside from information about greenhouse gases and sulphur emissions, the Technical Report No. 4/2013 also provided relevant data about other pollutants. In the case of NO_x emissions, the report forecasts that by 2020 NO_x emissions from maritime transport in the EU will be equivalent to NO_x emissions on land.

This is in line with the results published by numerous authors who warn about the special criticality of pollutant emissions from the SSS [6,7,10,11] and they suggest that the current regulations are insufficient to keep the sustainability of this kind of maritime traffic.

The use of the current technology to abate these pollutants [12] involves assuming the following cons: the ammonia slip for Selective Catalytic Reduction (SCR) systems which are compatible with petroleum fuel engines, the use of expensive fuels (MGO) or the methane slip derived from the use of gas engines. These relevant disadvantages do not seem to ensure the environmental feasibility of the intermodal chains with seaborne transport. In this latter case, the analysis of Liquefied Natural Gas (LNG) as a possible solution has been the subject of detailed studies in recent years. Nonetheless, the results of these studies have been inconclusive: the methane slip is especially significant for the SSS [10] and the use of LNG by itself is not able to provide emission levels close to Euro VI requirements [12]. Additionally, according to Acciaro (2014) [13], the reduced price of this fuel along with the reduction in maintenance costs associated with it [14], does not compensate the high investment required in the retrofitting of the vessels.

Growing concerning about the economic consequences of the implantation of the last ECA regulations in Europe on the competitiveness of SSS [9], joint with the uncertainties about their technological solutions (shown in the previous paragraphs), has forced to asses in depth the selection of the most suitable propulsion plant for SSS activity.

Culliane and Culliane (2013)[9] cautioned against undermining the inherent environmental advantage of shipping versus other modes of transport. In this respect, they remarked the importance of the analysis of the relative competitiveness of the SSS versus other transport modes as a consequence of the implementation of the ECA proposals in the E.U. In the same sense, Bengtsson et al. (2014)[11] have argued that, for the correct selection of the most suitable fuel for SSS, it is necessary to consider not only the environmental impact (local ,regional and overall) and the fuel cost but also the competitive situation with other transport modes. In line with this approach, Hjelle (2010 and 2014) analysed the emissions of different propulsion plants for SSS in terms of relative competitiveness versus trucking. The author concluded that, in the SSS operation the disadvantage in terms of NO_x and SO_2 emissions for the intermodal chain is evident. Only when the distances are significantly less for the intermodal chain the sustainability can be favourable to the intermodality [6]. Additionally, SSS might be superior to trucking alternatives when it comes to carbon emissions under given circumstances, but not always [7].

Therefore, this paper tries to provide a 'support decision tool' for the optimization of container fleets, their propulsion plants and their fuels, in order to maximize the opportunities of success of intermodal transport through MoS against the unimodal alternative. To this end, a mathematical model that had been previously developed had to be modified in order to assess the performance of the transport alternatives operating under the normative context assumed in this study (this is, the Euro-VI technology for the trucks and ECA regulations for the maritime stretch). With this modification, the initial capacities of the model (calculation of total costs, times and environmental costs for the transport modes) were widened by enabling the assessment of the current available technology to meet the ECA requirements [11,12]: heavy fuel oil (HFO) engines (Tier III) with scrubber, marine gas oil (MGO) engines (Tier III), and gas engines operating with LNG.

From the resolution of this model for a particular transport network between Spain and France, the performance of the intermodal chain operating with optimized vessels, different propulsion plants and fuels will be analysed. Since the model is a multiobjective model with linear and non-linear restrictions, an Evolutionary Algorithm (EA) has been used for its resolution. Afterwards, due to the high dependence of the results achieved on the fuel prices, a sensitivity analysis was carried out with the intention to meet the reliability of the results reached.

While it is necessary to be prudent before generalizing findings obtained from a particular case, this paper provides further information about the appropriateness of LNG use for SSS focused on the performance of the whole intermodal chain. Whereby, the conclusions are useful not only for the ship owners but also for the policy makers.

2. Literature review

Hjelle (2010) [6] identified the lack of efficient regulations for SSS as the main reason of its loss of competitiveness versus trucking (disadvantage in terms of NO_x and SO_2 emissions for the intermodal chain). In 2014 the same author broadened the study by comparing the CO2 emissions for SSS and road transport. The results for SSS were significantly higher than expected. The CO2 emission values widely exceeded those published in international policy papers (e.g. see the second IMO GHG study published by IMO Marine Protection Committee in 2009). Bengtsson et al (2014) [11] remarked that, despite of the fact that NOx emissions are the dominant contributor to the environmental impact of SSS, the stricter international rules (MARPOL Annex VI, Regulations for the

Prevention of Air Pollution from Ships, regulation 14, from January, 2015) with application to the EU (SECA zones) do not provide a significant decrease of NO_X emissions. Through this reality the authors justify the need of a singular regulation for SSS. Culliane and Culliane (2013) [9] concluded that the current and planned regulatory regime for the atmospheric emissions from ships posits that a greater market regulation is required. Additionally, they emphasize the economies of scale in pollutant emissions according to the sizing of the vessels and therefore the sensibility of the SSS in this regard. Brynolf et al. (2014) [12] remarked the need for regulation of additional pollutants in the maritime transport to match it with the stringency level of the European transport road: PM emissions and those pollutants derived from the application of abatement systems.

Thus, taking into account the broad consensus about the special environmental impact of SSS, and the evolution of the European environmental policy for the maritime transport, the authors foresee that the European environmental regulation will go beyond the adoption of the standards for the Emission Control Area (ECA) of the IMO and maximum maritime transport pollutant levels will be approached to those of the European road transport in the near future.

Nonetheless, the current technical solutions to meet the ECA requirements presents significant disadvantages. Brynolf et al. (2014) [12] evaluated compliance with ECA regulations through all available technological alternatives used in combination with marine bunker fuels and different marine engines which specifically are: Heavy fuel oil –HFO- combined with SCR -selective catalytic reduction- and a scrubber, Marine gas oil –MGO- combined with SCR and Liquefied natural gas –LNG-. As a result of this analysis, SCR was found to be a consolidated and effective technology to meet IMO Tier III regulation (which was enforced in ECAs from 2016 to 2021) whereas the scrubber performance still needs further verification. Moreover, the lack of specific regulation for the ammonia slip from the use of selective catalytic reduction (SCR) and for the methane slip from LNG engines emerges as an additional inconvenience. Elgohary et al. (2015) [14], after a similar analysis (fuel consumption, cost saving and emissions as drivers) concluded that LNG had proved to be better than other fuels due to fuel cost reduction and a decrease in emissions. The E.U opinion is also favourable about supporting the LNG usage for SSS. The EU has committed itself to establishing infrastructure that will allow LNG to be available to ships in all of its 144 maritime and inland ports by 2025[9]. Furthermore, some European countries already adopt additional measures in this sense, such as the Norwegian government funding the difference in construction costs for LNG-fuelled ferries [9].

Even though the LNG seems to be a promising solution, this also involves significant disadvantages. Aside from the inconvenient methane slip, Acciaro (2014) [13] noted that LNG development is critically dependent on its future price as well as a reduction of the capital costs of setting it up. In fact, Acciaro recommended deferring the investment in LNG plants as a strategy and he noted that policy makers play a critical role in its support: by maintaining of LNG prices at favourable levels and avoiding ambiguity on regulation.

3. The model

The considered transport network responds to a 'many to many' transport model [4,15], where the MoS will be assumed to be the trunk haul of the intermodal chains (DM_{mk}; $\forall m \in M \wedge \forall k \in K$, see Figure 1, see Appendix1 as well) between the port on one coast (m) and the port located on another coast (k), which will be regarded as the consolidation centres (hubs) of the network, whereas the capillary hauls (DR^b_{zm}; $\forall z \in Z \wedge \forall m \in M$ and DR^b_{kd}; $\forall k \in K \wedge \forall d \in DD$) will represent the land stretches among the hubs and the nodes (production/reception centres). For the definition of the nodes (z and d), the most populated cities per region that can be reached from the coast are considered (a population criterion) and are assumed to be the main production centres of container cargo and receivers. The probability of freight distribution among the capillary hauls on land, the probability of departure (X_z; $\forall z \in Z$) and delivery probability (X_d; $\forall d \in DD$) on both coasts was calculated on the basis of population criteria as well.

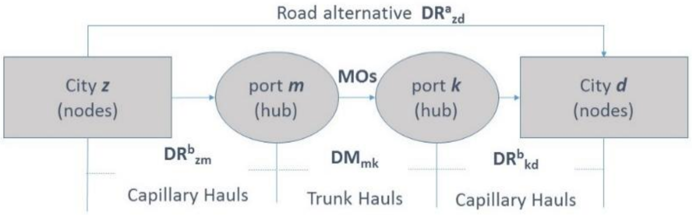

Figure 1: Configuration of the transport networks

The mathematical model used in this work is a modification of the model introduced by Martínez-López et al (2015,2016) [4,16], which was able to define realistic container vessels as being between 85 and 200m in length between perpendiculars. In previous versions, the model was able to define optimized vessels in a technical and operative form in order to maximize the advantage in total costs (F1), times (F2) [4], and externalities (F3) [16] of the intermodal chain versus the unimodal alternative. This model was previously applied to different frameworks, but taking in all cases as a fixed option the propulsion plant and its fuel (in every case).

For the optimization process, the initial model assesses and compares both intermodal and unimodal transport (per ton moved and trip).

Notwithstanding the numerous variables handled by this model (more than 150) only six of them are identified as non-dependent (See Appendix I):

- Compatible cargo units with container vessels (PP={1,…,p}): TEUs and FEUs
- Cargo handling system (GG={1,…g}): vessel cranes or port cranes.
- Bow thruster installation (BB={1,…,b}): Yes or No
- Cargo capacity of the vessel (G_p; $\forall p \in PP$),
- Speed of the vessel (VB)
- Number of vessels in the fleet (NB)

Thus, the necessary characteristics to define the optimized vessels: length (L), breadth (B), depth to the upper deck (D), gross tonnage (GT), deadweight (TPM), propulsion power (PB), number of engines (NME_i;$\forall i \in I$), kind of propeller (TP_h; $\forall h \in H$), number of shaft lines ($NSL_n;\forall n\in N$) (see the Appendix I) among others, are calculated from the non dependent variables.

This initial model has been modified to respond to the objective addressed in this paper: the evaluation of the suitability of different propulsion plants by taking into account the environmental impact on the whole intermodal chain. In order to achieve this, one additional non-dependent variable was firstly introduced in the model: the kind of propulsion plant ($TMM_e;\forall e\in EE$, see Appendix I), that is:

- TMM_1: medium speed four-stroke diesel engine with MGO (Tier-III).
- TMM_2: medium-speed four-stroke diesel engine (Tier-III) with scrubber by operating with HFO.
- TMM_3: LNG propulsion plant.

The inclusion of this new parameter has involved:

1. Modification of the calculation process for the cargo capacity of the vessels ($G_p;\forall p\in PP$). The arrangement of the scrubber system for TMM_2 and, especially, the LNG tanks for the TMM_3 alternative (the standard dimensions for the gas tanks type C provided by Wärtsila -LNGPac[4]- along with the IMO IGF-Code, 2015[5] and the design rules demanded by the American Bureau of Shipping-ABS rules, 2015[6]- for the arrangement of the LNG tanks) will condition the general arrangement of the vessels and as a consequence of this, a reduction in their cargo capacity ($G_p;\forall p\in PP$ [12]) with a subsequent impact on the competitiveness of the intermodality
2. Enlargement of the initial calculation of the externalities (F3). It has been necessary to add pollutants and modifying the calculation process by taking into account the 2015 'transport reality'.
3. Modification of the cost calculation (F1). The consideration of the different possibilities of propulsion plants does not only influence the building cost (*CC*) and therefore the capital costs [17], but also on the fixed and variable costs for the operation of the fleet [18,19], which enables the calculation of the competitiveness of the intermodality in terms of costs (F1).

3.1 Objective functions, restrictions and the resolution

The resolution of the mathematical model provides the most suitable fleet, propulsion plant and fuel to maximize the opportunities of success of intermodality against unimodality in terms of costs (F1), times (F2, [20]) and externalities (F3). These objective functions (maximization of the advantage for intermodality) are mathematically shown in the equations 1,7 and 14 (see Appendix I). Thus, the greater the positive value of the functions, the bigger the advantage for intermodality.

$$F1 = \max\,(CU - CMU) \tag{1}$$

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[4] http://www.wartsila.com/products/marine-oil-gas/gas-solutions/fuel-gas-handling/wartsila-lngpac (Accessed, January, 2016)

[5] The "International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels" adopted by IMO's Maritime Safety Committee (MSC) in June 2015 entered into force on 1 January 2017

[6] "Guide for Propulsion and Auxiliary Systems for Gas Fueled Ships". ABS. Rules & Guides. May 2015

$$CU = RE + \left(\sum_{z=1}^{z}\sum_{d=1}^{\mathrm{d}}(X_z \times X_d \times DR_{zd}^{a})\right) \times \frac{CK_p}{P_p}; \qquad \forall p \in PP \wedge \forall d \in DD \wedge \forall z \in Z \tag{2}$$

$$CMU = \sum_{a=1}^{a} CMU_{\mathrm{a}} \qquad \forall a \in A \tag{3}$$

$$CMU_1 = RE_1 + \left(\sum_{z=1}^{\mathrm{z}}(X_z \times DR_{zm}^{b})\right) \times \frac{CK_p}{P_p} \qquad \forall p \in PP \wedge \forall m \in M \wedge \forall z \in Z \tag{4}$$

$$CMU_2 = RE_2 + \left(\sum_{d=1}^{\mathrm{d}}(X_d \times DR_{kd}^{b})\right) \times \frac{CK_p}{P_p} \qquad \forall p \in PP \wedge \forall k \in K \wedge \forall d \in DD \tag{5}$$

$$CMU_3 = RE_3 + \left(\frac{1}{G_{\mathrm{p}} \times P_p \times Ntrips}\right) \times \sum_{c=1}^{12} CT_c \qquad \forall p \in PP \tag{6}$$

The calculation of the unimodal cost (*CU,* see equation 2) is dependent on the distance (DR^{a}_{zd}, see Figure 1) between pairs of nodes ($\forall z \in Z$ and $\forall d \in DD$, Appendix I), their distribution probabilities (X_z and X_d,), the unitary costs for road transport (CK_p;$\forall p \in$PP) the external costs for the unimodality (RE) [4,16] and the weight of the cargo units (P_p, $\forall p \in PP$).

The addition of the maritime stretch costs (CMU_3) and the road haulage costs (CMU_1 and CMU_2) leads to the intermodality costs (*CMU,* see equation 3). The calculation process for the costs of the road hauls is the same as the costs of unimodality, but takes into account their distances between nodes and hubs (DR^{b}_{zm}, $\forall z \in Z$; $\forall m \in M$ and DR^{b}_{kd}; $\forall k \in K$ $\forall d \in DD$ see Figure 1). The calculation of the maritime stretch costs (CMU_3) requires the calculation of the minimum required freight for the fleets [19]. This involves the consideration of all the cost items related to the maritime transport (CT_c, , $\forall c \in C$, see Appendix I), which are dependent on the technical and operative features of the fleets. The selection of the propulsion plant has special relevance due to the cost of its installation [21], maintenance [14,22], possible reduction of the cargo capacity [23]and consumption costs (unitary costs of the fuels).

In line with previous experience, the technical features of optimized fleets for SSS (fast and small vessels [4,16,24]) and the expected power required for the propulsion of the vessels (between 7,000 and 8,000 hp) leads to the installation of medium-speed four-stroke propulsion engines that are compliant with IMO Tier III in all cases (to meet the ECA zone requirements). That is, the installation of SCR systems and the use of fuels with low sulphur content (Marine Gas Oil-LSMGO- with a 0.1% sulphur content on a mass basis, for TMM_1, HFO with 2.7% sulphur content in the fuel for TMM_2) is necessary for all fuel-based engines. Additionally, for the alternative TMM_2, the establishment of a scrubber system is necessary.

$$F2 = \max\,(TVU - TVM) \tag{7}$$

$$TVU = \sum_{z=1}^{z}\sum_{d=1}^{d}\left(X_z \times X_d \times \left[\left\lfloor \frac{\left\lfloor \frac{DR_{zd}^{a}}{9 \times VT} \right\rfloor \times 0.75 + \frac{DR_{zd}^{a}}{VT}}{9} \right\rfloor \times 24 + \left[\left(\frac{\left\lfloor \frac{DR_{zd}^{a}}{9 \times VT} \right\rfloor \times 0.75 + \frac{DR_{zd}^{a}}{VT}}{9}\right) - \left\lfloor \frac{\left\lfloor \frac{DR_{zd}^{a}}{9 \times VT} \right\rfloor \times 0.75 + \frac{DR_{zd}^{a}}{VT}}{9} \right\rfloor\right] \times 9\right]\right) \tag{8}$$

$$TVM = \sum_{a=1}^{a} TVM_a \qquad \forall a \in A \tag{9}$$

$$TVM_1 = \sum_{z=1}^{z}\left(X_z \times \left[\left\lfloor \frac{\left\lfloor \frac{DR_{zm}^{b}}{9 \times VT} \right\rfloor \times 0.75 + \frac{DR_{zm}^{b}}{VT}}{9} \right\rfloor \times 24 + \left[\left(\frac{\left\lfloor \frac{DR_{zm}^{b}}{9 \times VT} \right\rfloor \times 0.75 + \frac{DR_{zm}^{b}}{VT}}{9}\right) - \left\lfloor \frac{\left\lfloor \frac{DR_{zm}^{b}}{9 \times VT} \right\rfloor \times 0.75 + \frac{DR_{zm}^{b}}{VT}}{9} \right\rfloor\right] \times 9\right]\right) \tag{10}$$

$$TVM_2=\sum_{d=1}^{d}\left(X_d\times\left[\left\lfloor\frac{\left\lfloor\frac{DR_{kd}^{b}}{9\times VT}\right\rfloor\times0.75+\frac{DR_{kd}^{b}}{VT}}{9}\right\rfloor\times24+\left[\left(\frac{\left\lfloor\frac{DR_{kd}^{b}}{9\times VT}\right\rfloor\times0.75+\frac{DR_{kd}^{b}}{VT}}{9}\right)-\left\lfloor\frac{\left\lfloor\frac{DR_{kd}^{b}}{9\times VT}\right\rfloor\times0.75+\frac{DR_{kd}^{b}}{VT}}{9}\right\rfloor\right]\times9\right]\right) \tag{11}$$

$$TVM_3=\sum_{s=1}^{s}TVB_s \qquad \forall s\in SS \tag{12}$$

$$TVB_1=DM_{mk}/(VB\times1.85)^{7} \qquad \forall m\in M\wedge\forall k\in K \tag{13}$$

The estimation of the time invested in the unimodal transport (*TVU,* equation 8) and the times for the road hauls in the intermodal chains (TVM_1 and TVM_2 see Appendix I) for equation 7 were calculated by considering the European Normative on the maximum speed for trucks (European Directives 92/24/EC, 92/6/EC) and minimum breaks for the resting of the drivers (Regulation 561/2006 of European Parliament). The calculation of the time invested in the intermodal transport (*TVM*) integrates, aside from the road haulage times, the time invested in the maritime stretch (TVM_3). This integrates the shipping time (TVB_1;, dependent on the DM_{mk};$\forall m\in$M$\wedge\forall k\in$K, and the speed of the vessel *VB,* see equation 13 and Appendix I), the berthing time (TVB_2) which involves the loading/unloading process, and finally the maneuvering time while in port (TVB_3) [16,25,26].

$$F3=\max\,(RE-MUE) \tag{14}$$

Equation 14 ensures the competitiveness in terms of externalities (environmental costs), but the calculation method for the costs for each transport mode, unimodal (*RE)* and multimodal (*MUE* Appendix I), is provided in detail in the following section (3.2).

In order to ensure the feasibility of the optimized fleet and its utility, 13 restrictions (linear and nonlinear restrictions) were imposed on the model [4]; 9 to ensure the technical feasibility of the vessels; 3 ensure to guarantee the service requirements demanded by transport needs and one restriction aimed at avoiding the operation of the vessels under High-Speed Craft condition (High-Speed Craft Code MSC 36(63) and SOLAS, chapter X) due to the numerous limitations linked to this kind of operation during shipping.

The model can be defined as a mixed-integer and nonlinear problem with numerous nonlinear constraints and a multi-objective model. Due to the complexity of its resolution, the NSGA-II (Non-dominated Sorting Genetic Algorithm-II*)* was used where the independent variables of the model are the chromosomes of the population of the NSGA-II. During the evolutionary process the genes reach values of between -1 and 1 due to the use of JEAF (A Java Evolutionary Algorithm Framework) used in this work model [27]. In each experiment 50 independent tests were performed. In order to compare each test, the hyper volume measurement [28] was used because it allows us to evaluate different performances of an algorithm through the comparison of the Pareto fronts (F1 versus F2) obtained by using a unique value (F1 is better than F2 if the hypervolume of F1 is greater than the F2 hypervolume). Finally, the stopping criterion for the Evolutionary algorithm has been the maximum number of calls to the evaluation functions: 10000.n, where n is the dimension of the problem (number of the non-dependent variables for the optimization).

3.2 The calculation of the externalities *F3*

Even though the external costs (externalities) in transport involve different items (noise, accidents, congestions, etc), in this study only the environmental costs have been considered

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[7] 1.85km=1 knot

as externalities. This research has adapted the model introduced by Martínez-López et. al (2016) [16] to calculate the environmental costs for unimodal and intermodal transport, and therefore to evaluate the objective function F3. The original model [16] assumed the Tier I method suggested by The European Environmental Agency (EEA) through its regular publications ''EMEP/EEA air pollutant emission inventory guidebook'' [29] to calculate the externalities related to road transport. According to the EEA, the tiers represent a growing level of methodological complexity: Tier I (the simplest one), Tier II (intermediate) and Tier III (the most accurate).

Despite the fact that the Tier II and Tier III are the most recommendable ones, due to the high level of data required for their application (kind of via, technology of the trucks, the engine operation conditions, etc), they were ruled out in the initial model of Martínez-López et. al (2016) [16]. Tier I uses default emission coefficients for all EU member states (2005), considering the fuel as the activity indicator along with the average fuel-specific emission coefficients (2009). Due to the reference dates assumed by this approach, the application of Tier I to calculate the emission coefficients (*EGU,* see Appendix I) of Euro VI HDV (this technology is compulsory from 2014) will provide higher values than those calculated through more accurate tiers (Tier II and Tier III). In order to resolve this, the initial model was adapted to calculate the external costs through the Tier II method. The Tier II approach considers emission standards for the main pollutants affected by the vehicle technology ($PM_{2,5}$ and NO_x) taking into account different HDV technologies (emission control legislation) and kinds of fuels.

Another important deficiency of the initial model is the fact that it did not consider the assessment of the CH_4 emissions for the calculation of the environmental costs, this involved that the methane slip [10]- namely the unburnt methane from the combustion of LNG and methane leakage [11,12,22]- was not evaluated in gas engines.

In light of the above, the Martínez-López et al (2016) model [16] has been modified. Thus, the pollutants currently assessed are: (U ={1, …, u}, see Appendix I): NO_x (ozone precursors), SO_2 (acidifying substances), $PM_{2.5}$ (particular matter mass), greenhouse gases CO_2 and CH_4.

Euro VI technology (that has been compulsory in the EU since January 2014) was assumed for Heavy Duty Vehicles (HDV) N3 (Annex II, Directive 2007/46/EC of the European Parliament), which are able to transport the weights associated with the compatible cargo units with containerships (TEUs and FEUs).

Thus, the calculation process Tier II [29] for the environmental costs (externalities) in the road haulages (*RE* in €/ t and trip, and CET_{pv} in €; $\forall p \in PP \wedge \forall v \in V$ see equations 15-17 and Appendix I) and in the road hauls in the intermodal chains (RE_1 and RE_2 on every coast[8]) has taken into account EuroVI technology for the estimation of the fuel consumption of trucks (FC_p; $\forall p \in$ PP- gr fuel/km) and for emission coefficients (EGU_{up}; $\forall u \in U \wedge \forall p \in PP$, see Appendix I and Appendix II) related to $PM_{2,5}$ and NO_x (pollutants affected by vehicle technology). Whereas the Tier1 process was used to obtain the emission coefficients that originate directly from the fuel and lubricant combustion: CO_2 and SO_2 takes into account the kind of fuel and the year [29].

$$RE = CET_{pv} \times (1 / P_p) \qquad \forall p \in PP \wedge \forall v \in V \qquad (15)$$

$$CET_{pv} = \sum_{u=1}^{u} CET_{upv} \qquad \forall p \in PP \wedge \forall v \in V \qquad (16)$$

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[8] The equations 15-17 are applicable but with the capillary distances

$$CET_{upv} = \sum_{f=1}^{f} (\mathrm{CF}_{\mathrm{ufv}} \times \mathrm{FC}_{\mathrm{p}} \times \mathrm{EGU}_{\mathrm{up}} \times 10^{-6} . \mathrm{X}_{\mathrm{f}} \times (\sum_{\mathrm{z}=1}^{z} \sum_{\mathrm{d}=1}^{d} (\mathrm{X}_{z} \times \mathrm{X}_{d} \times \mathrm{DR}_{zd}^{a}))); \quad \forall u \in U \land \forall p \in PP \land \forall v \in V \qquad (17)$$

The unitary costs of the considered pollutants are those published by Korzhenevych et al. (2014) [30] for 2010 and these were updated to 2015 values, according to the CPI of the countries affected by the transport. These unitary costs (CF_{ufv}; $\forall u \in \mathrm{U} \land \forall f \in \mathrm{FF} \land \forall v \in \mathrm{V}$-€/kg pollutant, see Appendix I and II) are dependent on, besides the kind of pollutant ($\mathrm{U}=\{1, \dots, u\}$), on the country which supports the transport service ($\mathrm{FF} = \{1, \dots, f\}$) and on the kind of zone (metropolitan and urban $V = \{1, \dots, v\}$). Due to this dependence on the transited countries, it has been necessary to introduce a probability distribution factor to determine the percentage of the total distance of the transport that corresponds to each country (X_f; $\forall f \in \mathrm{FF}$; see Equation 6 and Appendix I). For the CO_2 unitary cost, the central value was considered, whereas the unitary cost of the CH_4 was assumed, according to its Global Warning Potential regarding CO_2 [30].

The environmental costs (externalities)for the intermodal chains (MUE, see equation 14 and Appendix 1) integrate the capillary hauls costs (RE_1 and RE_2) to the costs of the trunk haul (maritime stretch, CEM in € -equation 18- or ME in €/trip and ton-equation 24, see Appendix 1). Likewise, CEM (see equations 18-23) is the sum of the environmental costs during all operational stages ($\mathrm{SS} = \{1, \dots, s\}$; [26], see Appendix 1): free sailing (CEM_1), maneuvering (CEM_2, port pilot time, tug service time, and mooring time), and berthing (CEM_3, loading/unloading operations); the unitary costs of the pollutants in the maritime transport must include this new dependence (CF_{sufv}; $\forall s \in \mathrm{SS} \land \forall u \in \mathrm{U} \land \forall f \in \mathrm{FF} \land \forall v \in \mathrm{V}$-€/kg pollutant -equations 21 and 23-see Appendix I and II). Indeed, the unitary costs applied to the sailing stage are uniquely dependent on the kind of European sea [30], (see Appendix II). The emission factors for the container vessels (EG_{su}; $\forall s \in \mathrm{SS} \land \forall u \in \mathrm{U}$ in kg/nm and in kg/h-equations 19, 21 and 23, see Appendix I) have been estimated through the calculation tool for environmental emissions developed by the Technological University of Denmark and the University of Southern Denmark [31,33][9] for all pollutants except for CH_4.

$$CEM = \sum_{s=1}^{3} CEM_s \qquad \forall s \in SS \qquad (18)$$

$$CEM_1 = \sum_{u=1}^{4} (EG_{1u} \times DM_{mk} \times 0.54 \times CF_{1u}) \times N_{trips} + + PB \times EF_e \times LF_1 \times TVB_1 \times 10^{-3} \times CF_{15} \times N_{trips} \qquad \forall m \in M \land \forall k \in K \land \forall e \in EE \qquad (19)$$

$$CEM_2 = 0.5 \times N_{trips} \times \sum_{f=1}^{f} (CEM_{2f}) \qquad (20)$$

$$CEM_{2f} = \sum_{u=1}^{4} (EG_{2u} \times TVB_2 \times CF_{2ufv}) + PB \times EF_e \times LF_2 \times TVB_2 \times 10^{-3} \times CF_{25fv} \qquad \forall f \in FF \land \forall v \in V \land \forall e \in EE \qquad (21)$$

$$CEM_3 = 0.5 \times N_{trips} \times \sum_{f=1}^{f} (CEM_{3f}) \qquad (22)$$

$$CEM_{3f} = \sum_{u=1}^{4} (EG_{3u} \times TVB_3 \times CF_{3ufv}) + PB \times EF_e \times LF_3 \times TVB_3 \times 10^{-3} \times CF_{35fv} \qquad \forall f \in FF \land \forall v \in V \land \forall e \in EE \qquad (23)$$

$$ME = CEM / (P_p \times N_{trip} \times G_p) \qquad \forall p \in PP \qquad (24)$$

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[9] https://www.shipowners.dk/en/services/beregningsvaerktoejer/

The calculation of the CH_4 costs was based on the method suggested by the United States Environmental Protection Agency (US EPA,[14,22]), which takes into account (see equations 19, 21 and 23): the load factor of the main engine in each operational stage (LF_s; ∀s ∈ SS, see Appendix I and II), the propulsion power of the vessels (PB in kW); and the CH_4 emission factor given by the evaluated propulsion plant (EF_e; ∀e ∈ EE in g/kW.h,- equations 19,21 and 23- see Appendix I and II). For this last variable, the emission factor for CH_4 must take into account the methane slip. Despite the high degree of uncertainty about the quantification of the methane [10,11,12,33] and its dependence on the load factor of the engines [10,34], the model will assume an emission factor of CH_4 for dual engines operating with LNG (TMM_3) of $EF_3 = 5.79$ g/kWh [12,34,35] and for fuel-based engines of $EF_1 = EF_2 = 0.040$ g/kWh [10] (see Appendix II).

4. Application and results

The establishment of MoS between Spain and France on the Atlantic coast was regulated through an Intergovernmental Agreement that supported the operation of these MoS when they promoted the general interest (BOE Nº92, 2006)[36]. This is, a transport service with stoppages between 4 and 7 per week in every directions and a minimum yearly movement of 1,530,000t. This MoS proves to be an interesting application case as the intermodal distance is significantly less than the unimodal distance (see Figure 2). This characteristic leads to clear advantages for intermodality (when the MoS is operated with an optimized fleet [4]) not only in terms of time and cost, but also in terms of externalities [6,16]. Thus, the application case selected for this study was a transport network between Spain and France through the MoS Vigo (port *m*) and St. Nazaire (port *k*). The Spanish node is a single one in the city of Vigo (*z*) whereas the French nodes (*d*) are the cities of Paris, Lille, and Rennes (see Figure 2). Thus, in this case the initial ‘many to many’ transport model was simplified to a ‘one to many’ transport model [4].

Figure 2: Transport network in the application case

The updated model with the possibility of identifying of most suitable propulsion plant for the vessels (TMM_e;∀e∈EE) will be resolved for this transport network with 2015 data. This involves Euro VI trucks and input values of 2015 (see Appendix II). The technical features of the most suitable fleet for this transport network (see Table 1) are already known for 2010 data. These features were obtained through an optimization process with input values of 2010, Euro-I trucks and taking as a fixed parameter a MGO propulsion plant without abatement systems [16]. Thus, attempting to take advantage of this previous knowledge, the new optimization will be able to:

- Verify if the technical features of the fleet proposed as the most suitable for 2010 data are also proposed when the optimization is carried out with the updated model (2015).
- Determine the most adequate propulsion plant for the optimized fleet proposed.
- Indicate the realiability of the results achieved. For this, a sensitivity analysis will be carried out evaluating the dependence on the most influent parameter in the results: the unitary fuel prices.

Table 1: Technical features of the optimized fleet for 2010 data

Optimal Fleet (2010)	***Technical Features***
Kind of cargo unit	TEUs
Amount cargo (G_p)	201(G_1)
Vessel speed (Kn)	19.95
Bow thruster	No (MM_1)
Cargo handling system	Port cranes (MG_2)
Number of vessels (NB)	**3**
Yearly trips (N)	740
L (m)	80.55
B (m)	14.78
D to upper deck (m)	7.51
GT (Ton)	2627
Kind of propeller	Conventional screw (TP_1)
Shaft lines	1 (NSL_1)
Kind of main engine	Diesel Engine (Without abatement systems)
Number of engines	1 (NME_1)

Figure 3 shows the Pareto fronts obtained from the resolution of the updated model per kind of propulsion plant (regarded as a fixed variable in every optimization): squares for fleets with the TMM1 solutions (MGO in Tier III-engines), triangles for TMM2 solution (HFO, Tier III-engine and scrubber) and crosses for TMM3 solution (dual LNG engine). In such a way, the performance of the same fleets (with the same technical features) but with different propulsion plants can be compared. Every Pareto front collects a group of optimal fleets with a kind of propulsion plant ($TMM_e;\forall e\in EE$, see Appendix I). The vessels proposed in the Pareto fronts (See Figure 3) are in the following ranges of length, cargo capacity of the vessel (number of TEUs) and speed of the vessels, respectively: $77 \leq L \leq 89$ m; $173 \leq NC \leq 238$ TEUs; $19.4 \leq VB \leq 27.7$ knots. Since the characteristics of the fleet obtained with 2010 data (see Table 1) are within these ranges, this fleet solution is one of the optimized fleets for 2015 data.

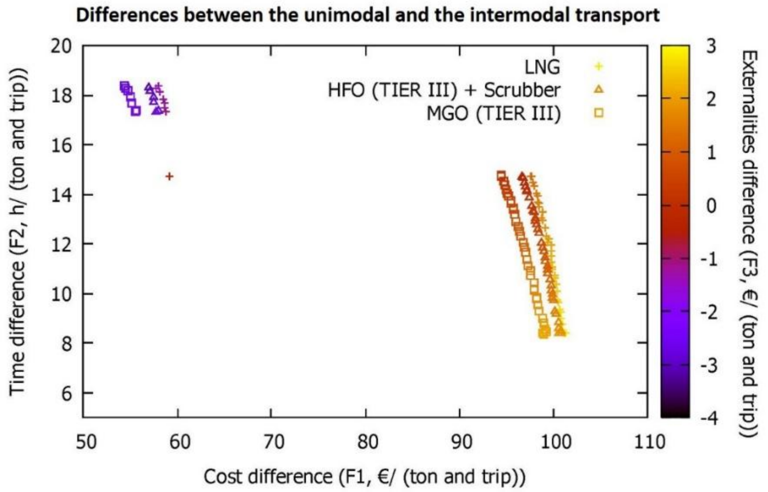

Figure 3: Pareto fronts for the optimization of the fleets by considering every type of propulsion plant as a fixed variable

It is noteworthy that the most competitiveness results found for fleet (see Figure 3) are made up of vessels with LNG propulsion system (crosses). The fleets proposed with LNG propulsion plants also articulates the most sustainable intermodal chains (the color of the crosses is closer to yellow than the other alternatives) and the most competitive ones in terms of total costs (F1). The other solutions for fleets based on petroleum fuel engines (TMM_1 and TMM_2, squares and triangles in Figure 3) prove to be less competitive on total costs (F1) and externalities (F3).

Table 2 shows the competitiveness results (F1, F2 and F3) for the suggested fleet (2010 data) when this is evaluated according to the updated model (2015 data) for every propulsion plant.

Table 2: Competitiveness results of the intermodal chains operated in 2015 with an optimized fleet with different propulsion plants

Type of main engine	**Dual engine (LNG) (TMM_3)**	**Tier-III engine+ Scrubber(HFO) (TMM_2)**	**Tier-III engine (MGO) (TMM_1)**
F_1 *(€/t per trip)*	101.33	100.78	99.16
F_2 *(h per trip)*	8.42	8.40	8.55
F_3 *(€/t per trip)*	2.85	1.86	2.05

Contrary to the expectations, the option with the highest capital costs (TMM_3, LNG based engines) has provided the best results in terms of costs (F1). This is mainly due to the fact that this initial investment is balanced with reduced fuel prices (see Appendix II) and moderate maintenance costs [14, 21,22] in contrast with the petroleum fuel engines options. Opposite to this, the alternative with the lower investment cost (TMM_1, Tier-III MGO propulsion plant [12]) offers the intermodal chains with the least advantage in terms of costs due to the high unitary cost for its fuel (Marine Gas Oil-LSMGO- with a 0.1% sulphur content on a mass basis).

According to the Figure 3 the results obtained for competitiveness in times and costs (F1 and F2) are especially close for those fleets with LNG engines and with HFO Tier-III engines with scrubber, only their differences in terms of the environmental costs (externalities) remain significant (see Table 2).

Indeed, the previous analysis suggests that a dual engine by operating with LNG (TMM_3) is the most suitable propulsion plant for the feeder vessels in this application case (a base scenario). Nonetheless, previous authors such as Brynolf et al (2014) [12] or Acciaro (2014) [13] (among others) have already cautioned about the high dependence of its profitability on differential between the prices of LNG and conventional maritime fuels. In the same sense, the Directorate-General for Mobility and Transport of the European Commission (2015) [37] concluded that the LNG propulsion plant is an attractive option to comply with ECA regulations when the fuel price difference is favorable to the LNG.

In turn, the high difficulty in predicting trends in fuel prices (due to their volatility [13,23]) leads to an increase in the uncertainty level. Therefore, the current results (see Table 2) and the performances obtained (see Figure 3) are insufficient to help draw broader conclusions about the suitability of the possible propulsion plants for MoS fleets operating in an ECA regulation context. Consequently, in order to provide further information about the reliability of the results obtained, new optimizations processes were carried out for different scenarios. Every scenario assumed different prices for LNG (within a 20% variation range of the base value, see Table 3) but taking constant prices for the petroleum fuels. In such a way that the scenarios show differences of prices between fuels and the LNG.

Table 3: Fuel prices considered for the sensitivity analysis (€/l)

Fuels	***Scenario 1(-20%)***	***Scenario 2 (Base Case)***	***Scenario 3 (+20%)***
LSMGO (0.1% Sulphur) (*TMM1* alternative)	0.208	0.208	0.208
IFO380 (Max. 3.5%Sulphur bunkers) (*TMM2* alternative)	0.350	0.350	0.350
LNG (Max. 3.5%Sulphur bunkers) (*TMM3* alternative	0.000164	0.000205	0.000246

(Source: from www.shipandbunker.com for prices at the Rotterdam port and were the maximum prices of the last quarter of 2015. The LNG price was obtained from the original price of 7 $/mmbtu)

Figure 4 shows the Pareto fronts obtained for the different scenarios evaluated. The optimizations in the scenarios 1 and 2 (where the fuel price differences are larger than the base case or the same, respectively) offer very few solutions of fleets based on petroleum fuel engines (TMM_1 and TMM_2, squares and triangles in Figure 3 and 4). These scarce fleets are made up of vessels with higher propulsion power requirements to offer a clear advantage in terms of time (F2) regarding trucking. This advantage attempts to balance the high external costs of these solutions (F3). Consequently, the proposed fleet based on petroleum fuel engines were less competitive on total costs (F1) and externalities (F3) than those with LNG propulsion plants (crosses in Figure 3 and 4). In other words, when the fuel price differences are the same or larger than the base case and the LNG propulsion plant is an option, it seems to be complicated to find fleets with petroleum fuel engines that are able to offer intermodal chains with environmental advantages regarding the road transport.

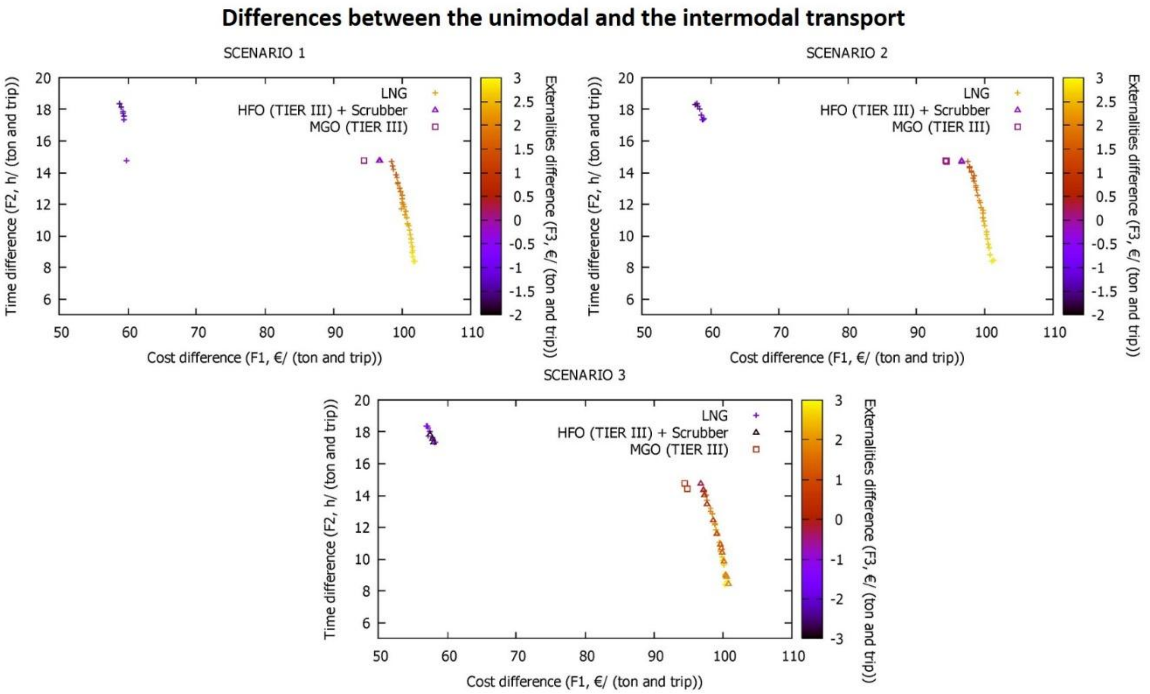

Figure 4: Pareto fronts for the optimization of the fleets by considering every type of propulsion plant as an optimization variable in different scenarios

Different behaviour is found when the fuel price difference is smaller than the base case (scenario 3). In that case, solutions of a fleet with a Tier III-engine and scrubber operating with HFO (*TMM₂*) offer the same competitiveness, in terms of cost (F1) and time (F2), as the solutions with LNG dual engines (*TMM₃*). Despite this, the sustainability of the intermodal chains remains higher when it is operated with vessels of LNG engines. This fact can be seen in the Table 4 where the competitiveness results for the optimized fleet (see Table 1) by operating under scenario 3 conditions are collected.

Table 4: Competitiveness results of the intermodal chains 2015 operated in scenario 3 with an optimized fleet

Type of main engine	**Dual engine (LNG) (*TMM₃*)**	**Tier-III engine+ Scrubber(HFO) (*TMM₂*)**
F_1 (€/t per trip)	100.69	100.78
F_2 (h per trip)	8.42	8.40
F_3 (€/t per trip)	2.85	1.86

According to the results obtained, there exists a clear advantage in environmental costs (externalities F3) of the intermodal chains operated by fleets propelled with gas-engines (*TMM₃*) compared to the those with vessels propelled with petroleum fuel engines (*TMM₁* and *TMM₂*), regardless of the fuel price scenario.

Therefore, notwithstanding the methane slip, the gas engine system proved to be the most competitive propulsion plant (see Table 2), followed by the MGO Tier-III engine (*TMM₁*) and finally the HFO Tier III engine with scrubber (*TMM₂*). This is so, by assuming a sulphur content of 2.7% for HFO and 0.1% for MGO and abatement capacities of 98% for SO_2 emissions and 55% for $PM_{2,5}$ emissions with the scrubber [23]. Moreover, this advantage for the LNG dual engines (*TMM₃*) is also significant in terms of costs (F1) when the difference in fuel prices is the same as, or within 20% variation range of, the base case. (see Table 4).

Regarding the vessels found during the optimization process, the optimized fleets proposed (see Figure 4) are made up of smaller and faster vessels when the fuel-based engines are installed. Furthermore, contrary to initial expectations [12], the reduction of the cargo capacity in holds by the gas tanks arrangement has been low. This is so because, due to the required propulsion power and maritime range of these vessels (SSS regime, around 540 nautical miles of range), only one standard tank is necessary. In fact, the volume of the smaller standard tank (100 m^3 LNGPac[10]) assumed for this study is grater than the required fuel capacity (around 54 m^3). This could involve that the loss of cargo capacity in the vessel is even less.

5. Conclusions

The unbalanced evolution of the environmental normative in the EU for the different transport modes in recent years, together with the highlighted results published by the European Environmental Agency about pollutant emissions from maritime transport have motivated a wide discussion about whether Short Sea Shipping should still be regarded as a green transport mode[5,6,]. This debate is especially pertinent, due to the fact that, no technological alternative has been indisputably identified to date, as the most sustainable propulsion plant for this kind of maritime transport. Consequently, the utility of MoS as part of intermodal chains for a more sustainable door-to-door transport solution in Europe is still under discussion.

In light of the above, this paper attempts to provide information about the influence on the competitiveness of the intermodal chains of possible propulsive solutions for SSS fleets operating in ECA zones. In order to achieve this, a mathematical model for the optimization of container vessels operating under MoS conditions, (previously developed by Martínez-López et al. in 2015 and 2016 [4,16]) was modified to evaluate the environmental impact of intermodal and unimodal transport in the 2015 framework of the EU. This involved to assume the Euro VI technology for trucks and the possible propulsion plants of the vessels to compliance with ECA requirements: Tier III-four-stroke diesel engine operating with MGO (TMM_1); a Tier III four-stroke diesel engine Tier-III with scrubber operating with HFO (TMM_2); and a four-stroke dual engine operating with LNG (TMM_3).

Due to the harmful methane slip associated with the gas-based engines, the CH_4 has been included in the traditional pollutants NO_x, SO_2, $PM_{2.5}$ and CO_2 of the model for its environmental evaluation (externalities assessment).

From the application of the model to a particular case in the Atlantic coast between Spain and France, some general conclusions can be extracted for SSS transport: notwithstanding

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[10] http://www.wartsila.com/products/marine-oil-gas/gas-solutions/fuel-gas-handling/wartsila-lngpac (Accessed January 2016)

the unbalanced normative framework, the intermodal chains operated with optimized fleets could be more suitable than the road alternative. Furthermore, due to the reduce range of the vessels under MoS conditions, the impact of the gas tanks arrangement on the cargo capacity of the container vessels when these are operating with LNG propulsion was not significant.

In addition, the performance of the optimization process in a base scenario for every kind of propulsion alternative indicates that, the dual gas engine (TMM_3) proved to be the best option for the three attributes evaluated (total costs, times and externalities). This solution is followed by HFO, a Tier-III engine with scrubber (TMM_2) when the total costs are attended. However, paying attention to the environmental costs, the MGO- Tier-III engine (TMM_1) would be in second place. This result was notable because, although the maintenance costs and the LNG price proved to be lower in comparison with other propulsion plants and fuels, the expected reduction of the cargo capacity for the gas tanks arrangement and the high initial investment in this propulsion plant led to serious discussions about the feasibility of the dual LNG engines [13].

Since the feasibility of LNG propulsion plant is highly conditioned on the gas prices in relation to other petroleum fuels [13,37], a sensitivity analysis was carries out in order to reduce the uncertainty about the results previously obtained. This analysis concluded that, the LNG dual engines offers not only an environmental advantage for SSS fleets (regardless of the scenario of fuel prices studied), but also a better performance in terms of costs when the fuel prices difference stays the same as, or within 20% variation range of, the base case (second quarter of 2015). Nonetheless, when this difference is reduced over this percentage HFO, Tier-III engine with scrubber (TMM_2) and LNG dual engines (TMM_3) offer equivalent performances in terms of costs.

Even though caution should be taken over generalizing these results, the findings of this paper may be applicable to intermodal chains involving similar distances.

Despite the uncertainties involved in gas operations (e.g. the availability of LNG in ports, technical standards, the second hand market for LNG vessels, among others), the Directorate-General for Mobility and Transport (European Commission, 2015 [37]) predicts between 2,500 and 4,000 LNG ships in the EU by the year 2030, using 1-5 million tonnes of LNG. This forecast assumes that, on the one hand fuel price differences will be larger than today for 2020-2030 and on the other hand, the upcoming stricter emission control area (ECA) regulations will have entered into force. If this reality finally comes about, the utility of the information provided by this paper as a ‘’support decision tool’’ will be maximum.

Future work will be strongly oriented to minimizing the impact of the uncertainties on the results. On the one hand, the volatility of the unitary costs for the pollutants warns about a possible modification of their relative weight on the external costs (F3 value). This reality will be evaluated through Monte Carlo simulations in order to determine further reliability for the achieved results. Finally, given the rapid evolution of the abatement technology by road, a broadening of the model introduced in this paper is expected to assess the feasibility of alternative fuels or additional propulsion solutions for the vessels (biofuels, fuel cells, etc).

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Appendix I: Glossary

Subscripts:

A=$\{1,..,a\}$	Different stretches which integrates the intermodal chains: the two capillary hauls (land legs in each coast) and one trunk haul (sea leg).
BB=$\{1,..,b\}$	Decisions about the installation of bow thruster in vessels: without and with bow thruster
DD=$\{1,..,d\}$	Destinations in land (French coast) for the transport network: Paris, Lille and Rennes
C=$\{1,..,c\}$	Set of cost items considered to reach the minimum required freight in the maritime transport: amortization costs, financing costs, insurance costs, maintenance costs, crew costs, fuel costs, ship duties in port, load duties
EE=$\{1,..,e\}$	Group of types of main engines: 1 for a medium speed four-stroke diesel engine with MGO (Tier-III), 2 for a medium-speed four-stroke diesel engine (Tier-III) with scrubber by operating with HFO, and 3 for an LNG propulsion plant for three.
FF =$\{1,...,f\}$	Group of countries affected by the transport system: Spain and France

$GG=\{1,..,g\}$	Alternatives for the cargo handling systems: crane vessels and port cranes
$H=\{1,..,h\}$	Set of propellers for the vessels: conventional screws and waterjets.
$I=\{1,..,i\}$	Number of main engines (from 1 to 4)
$K=\{1,..,k\}$	The unloading ports; French Port: St.Nazaire
$M=\{1,..,m\}$	The loading ports; Spanish Port: Vigo.
$N=\{1,..,n\}$	Number of shaft lines in the machine room (from 1 to 4)
$PP=\{1,..,p\}$	Kinds of cargo units for container vessels:TEUs and FEUs
$Q=\{1,..,q\}$	Group of possible ages for the fleet: 1, 6 and 14 years
$SS=\{1,...,s\}$	Group of operational stages in maritime transport: free sailing, maneuvering and berthing
$U=\{1,..,u\}$	Group of evaluated pollutants: NO_x, SO_2, $PM_{2.5}$ CO_2, and CH_4
$V=\{1,...,v\}$	Group of types of zones affected by the transport: metropolitan and urban
$Z=\{1,..,z\}$	Origins in land (on the Spanish coast) for the transport network: Vigo

Superscripts:

$MTA=\{^{a,\ b}\}$	Modal alternatives for transport: road haulage and intermodality, respectively.

Variables:

B	Breath of vessel (m)
C_e	Cost of the marine fuels (€/l)
CC	The building cost of vessels (€)
CEM	Yearly costs related to the externalities in the sea leg (€)
CEM_s	External yearly costs related to every operation stage of the sea leg (€);$\forall s\in SS$
CET_{pv}	Costs per trip related to the externalities in the unimodal transport (€) $\forall p\in PP \wedge \forall v\in V$
CF_{ufv};	Unitary costs of the pollutants in road transport (€/kg) $\forall u\in U \wedge \forall f\in FF \wedge \forall v\in V$
CF_{sufv};	Unitary costs of the pollutants in maritime transport (€/kg) $\forall s\in SS \wedge \forall u\in U \wedge \forall f\in FF \wedge \forall v\in V$
CK_p	Unitary cost for road haulage with one driver (€/km) (TEUs and FEUs)
CMU	Cost of intermodal chain (€/(t×trip))
CME	Cost of intermodal chain (€/(t×trip))
CMU_a	Cost of intermodal chain (€/(t×trip)) $\forall a\in A$
CT_c	Cost of the items which integrate the minimum required freight for the maritime transport (€); $\forall c\in C$
CU	Final cost of the unimodal transport alternative (€/(t×trip))
D	Depth to upper deck (m)
DM_{mk}	Maritime distance of the route (km); $\forall m\in M \wedge \forall k\in K$
DR^a_{zd}	Land distance for the unimodal alternative (km); $\forall z\in Z \wedge \forall d\in DD$
DR^b_{zm}	Distances of the capillary hauls for the intermodal chains from/to peripheral ports (km); $\forall z\in Z \wedge \forall m\in M$
DR^b_{kd}	Distances of the capillary hauls for the intermodal chains from/to great scale hub ports (km); $\forall k\in K \wedge \forall d\in DD$
E_q	Age of the vessel from the date of its construction; $\forall q\in Q$
EF_e	The emission factor for CH_4 in maritime transport (g/kW.h); $\forall e\in EE$
EG_{su}	The emission factors for all pollutants except CH_4 in maritime transport (kg/nm and in kg/h); $\forall s\in SS \wedge \forall u\in U$
EGU_{up}	The emission coefficients for pollutants in road transport (gr pollutant/kg fuel consumed); $\forall u\in U \wedge \forall p\in PP$
FC_p	Fuel consumption for road transport (g/km); $\forall p\in PP$
G_p	Cargo capacity of the vessel in units; $\forall p\in PP$
GT	Gross Tonnage of vessels (t)

L	Length of the vessel (m)
LF_s	The load factor of the main engine in each operational stage (%); $\forall s \in SS$.
ME	Environmental costs related to the externalities in the sea leg (€/trip and ton)
MG_g	Cargo Handling systems; $\forall g \in GG$
MM_b	Maneuvering means for the vessels (bow thruster) $\forall b \in BB$
MUE	Environmental costs (€/(t×trip)) associated to the multimodal transport
N_{trips}	Yearly number of trips for the fleet
NME_i	Number of main engines of the vessel; $\forall i \in I$
NB	Number of vessels
NMG_k	Maximum number of cranes for the unloading port; $\forall k \in K$
NMG_m	Maximum number of cranes for the loading port $\forall m \in M$
NSL_n	Number of shaft lines in a vessel; $\forall n \in N$
P_p	Weight of the cargo units (t); $\forall p \in PP$
PB	Propulsion power of the vessels (HP)
RE	Environmental costs (€/(t×trip)) associated to the road transport
RE_a	Environmental costs(€/(t×trip))associated to different stretches of intermodal chains; $\forall a \in A$
TMM_e	Kind of main engine for the vessels; $\forall e \in EE$
TP_h	Kind of propeller $\forall h \in H$
TPM	Deadweight of the vessel (t)
TVM_a	Time invested in one transport mode integrated in an intermodal chain (h); $\forall a \in A$
TVB_s	The time invested in operation stages during the maritime transport (h); $\forall s \in SS$
TVM	Time invested in the multimodal transport (h)
TVU	Time invested in the unimodal alternative (road haulage) (h)
VB	Speed of the vessel (Kn)
VT	Speed of truck (km/h)
X_d	Relative probability of cargo delivery in a node with respect to the other possible nodes on the French coast (%); $\forall d \in DD$
X_f	Percentage of the total land distance that belongs to each country (%); $\forall f \in FF$
X_z	Relative probability of cargo delivery in a node with respect to the other possible nodes on the Spanish coast (%);$\forall z \in Z$

Appendix II: *Values assumed for key inputs in the application case*

Table 5: Base Values for emission coefficients and inputs for calculation of emission factor CH4

CONCEPT	NOTATION		DESCRIPTION	VALUE	UNITS
Load factor	LF_s	LF_1	Load factor for free sailing	85%	%
		LF_2	Load factor manouvering	15%	%
		LF_3	Load factor for berthing	5%	%
Emission factor methane	EF_e	EF_1	Emission factor CH_4 for MGO engine (Tier III)	0.044	g/kWh
		EF_2	Emission factor CH_4 for HFO engine with scrubber (Tier III)	0,044	g/kWh

		EF_3		Emission factor CH4 for LNG dual engine	5.79	g/kWh
Fuel Features in the unimodal transport	FC_p	FC_1= FC_2		Average fuel consumption for Heavy Duty Trucks (16-32t) (Euro VI)	210	g/km
	EGU_{up}	EGU_{1p}	EGU_{11}= EGU_{12}	Emission coefficient NO_x for HDV with TEUs or FEUs	2	g/Kg fuel
		EGU_{2p}	EGU_{21}= EGU_{22}	Emission coefficient SO_2 for HDV with TEUs or FEUs	8.10^{-3}	g SO_2/kg fuel
		EGU_{3p}	EGU_{31}= EGU_{32}	Emission coefficient $PM_{2.5}$ for HDV with TEUs or FEUs	$5.7\ 10^{-3}$	g $PM_{2.5}$/Kg fuel
		EGU_{4p}	EGU_{41}= EGU_{42}	Emission coefficient CO_2 for HDV with TEUs or FEUs	$3.14\ 10^{3}$	gCO_2/Kg fuel
		EGU_{5p}	EGU_{51}	Emission coefficient CH_4 for HDV with TEUs	0.009	gCH_4/Kg fuel
			EGU_{52}	Emission coefficient CH_4 for HDV with FEUs	0.023	gCH_4/Kg fuel

Table 6: Values for unitary costs for pollutants in the seaborne stretch (2015)

CONCEPT	NOTATION				DESCRIPTION	VALUE	UNITS
Unitary costs of the pollutants	CF_{sufv}	CF_{1u}	CF_{11}		Unitary cost NO_x for free sailing	2,36	€/kg
			CF_{12}		Unitary cost SO_2 for free sailing	3,04	€/kg
			CF_{13}		Unitary cost $PM_{2.5}$ for free sailing	5,81	€/kg
			CF_{14}		Unitary cost CO_2 for free sailing	0,09	€/kg
			CF_{15}		Unitary cost CH_4 for free sailing	2,36	€/kg
		CF_{2ufv}	CF_{2u12}= CF_{3u12}	CF_{2112}= CF_{3112}	Unitary cost NO_x for manoeuvring and berthing in Vigo (Spanish urban port)	5,19	€/kg
				CF_{2212}= CF_{3212}	Unitary cost SO_2 for manoeuvring and berthing in Vigo (Spanish urban port)	7,37	€/kg
				$CF_{2312=}$= CF_{3312}	Unitary cost $PM_{2.5}$ for manoeuvring and berthing in Vigo (Spanish urban port)	50,17	€/kg
				CF_{2412}= CF_{3412}	Unitary cost CO_2 for manoeuvring and berthing in Vigo (Spanish urban port)	0,094	€/kg
				CF_{2512}= CF_{3512}	Unitary cost CH_4 for manoeuvring and berthing in Vigo (Spanish urban port)	2,35	€/kg
			CF_{2u21}= CF_{3u21}	CF_{2121}= CF_{3121}	Unitary cost NO_x for manoeuvring and berthing in St.Nazaire (French metropolitan port)	13,70	€/kg
				CF_{2221}= CF_{3221}	Unitary cost SO_2 for manoeuvring and berthing in St.Nazaire (French metropolitan port)	12,92	€/kg
				CF_{2321}= CF_{3321}	Unitary cost $PM_{2.5}$ for manoeuvring and berthing in St.Nazaire (French metropolitan port)	222,38	€/kg
				CF_{2421}= CF_{3421}	Unitary cost CO_2 for manoeuvring and berthing in St.Nazaire (French metropolitan port)	0,094	€/kg
				CF_{2521}= CF_{3521}	Unitary cost CH_4 for manoeuvring and berthing in St.Nazaire (French metropolitan port)	2,36	€/kg

(Source:’Update of the Handbook on External Costs of Transport , 2014 ‘’ updated to 2015)

Table 7: Base Values for unitary costs for pollutants in the road stretches

CONCEPT	NOTATION				DESCRIPTION	VALUE	UNITS
Unitary costs of the pollutants	CF_{ufv}	CF_{u1v}	CF_{u11}	CF_{111}	Unitary cost NO_x for metropolitan area in Spain	5,19	€/kg
				CF_{211}	Unitary cost SO_2 for metropolitan area in Spain	7.37	€/kg
				CF_{311}	Unitary cost $PM_{2.5}$ for metropolitan area in Spain	204.04	€/kg
				CF_{411}	Unitary cost CO_2 for metropolitan area in Spain	0.094	€/kg
				CF_{511}	Unitary cost CH_4 for metropolitan area in Spain	2.35	€/kg
			CF_{u12}	CF_{112}	Unitary cost NO_x for urban area in Spain	5.19	€/kg
				CF_{212}	Unitary cost SO_2 for urban area in Spain	7.37	€/kg
				CF_{312}	Unitary cost $PM_{2.5}$ for urban area in Spain	50.17	€/kg
				CF_{412}	Unitary cost CO_2 for urban area in Spain	0.094	€/kg

				CF_{512}	Unitary cost CH_4 for urban area in Spain	2.35	€/kg
		CF_{u2v}	CF_{u21}	CF_{121}	Unitary cost NO_x for metropolitan area in France	13.70	€/kg
				CF_{221}	Unitary cost SO_2 for metropolitan area in France	12.92	€/kg
				CF_{321}	Unitary cost $PM_{2.5}$ for metropolitan area in France	222.38	€/kg
				CF_{421}	Unitary cost CO_2 for metropolitan area in France	0.094	€/kg
				CF_{521}	Unitary cost CH_4 for metropolitan area in France	2.36	€/kg
			CF_{u22}	CF_{122}	Unitary cost NO_x for urban area in France	13.70	€/kg
				CF_{222}	Unitary cost SO_2 for urban area in France	12.92	€/kg
				CF_{322}	Unitary cost $PM_{2.5}$ for urban area in France	67.78	€/kg
				CF_{422}	Unitary cost CO_2 for urban area in France	0.094	€/kg
				CF_{522}	Unitary cost CH_4 for urban area in France	2.36	€/kg

(Source: ‘’Update of the Handbook on External Costs of Transport, 2014 ‘’ updated to 2015)

Table 8: Unitary costs for road transport and for marine fuels (2015)

CONCEPT	NOTATION		DESCRIPTION	VALUE	UNITS
Unitary costs for road transport	CK_p	CK_1	Unitary cost for road transport of HDV with TEU	1.2	€/kM
		CK_2	Unitary cost for road transport of HDV with FEU	1.3	€/kM
Base costs for marine fuels	C_e	C_1	Base Value for LSMGO (0.1% Sulphur)	0.208	€/l
		C_2	Base Value for IFO380 (Max. 3.5%Sulphur bunkers)	0.350	€/l
		C_3	Base Value LNG (Max. 3.5%Sulphur bunkers)	0.000205	€/l

(Source: from www.shipandbunker.com for prices at the Rotterdam port and were the maximum prices of the last quarter of 2015. The LNG price was obtained from the original price of 7 $/mmbtu .Observatory of freight transport by road (July, 2015 Report), Ministry of Development of Spain)