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ORIGINAL ARTICLE

A multi-objective mathematical model to select fleets and maritime routes in short sea shipping: a case study in Chile

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Abstract

This paper proposes a mathematical model for intermodal chains with seaborne transport, in which the optimization of a multi-objective model enables conflicting objectives to be handled simultaneously. Through the assessment of 'door-to-door' transport in terms of costs, time, and environmental impact, the most suitable maritime route and the optimized fleet are jointly proposed to maximize the opportunities for success of intermodal chains versus trucking. The NSGA-II algorithm is applied to resolve the model. The Pareto fronts obtained not only permit decision-making in the short-term but also enable long-term strategies to be defined according to the behaviour of these frontiers when sensitivity analysis is undertaken. A real-life case in Chile is studied to test the usefulness of the model. Aside from identifying the most suitable Motorway of the Sea with its optimized fleet for Chile, the application case has provided several significant findings to promote the intermodal option regardless of its location.

Keywords Short sea shipping · Motorways of the sea · Intermodal chains · Multi-objective optimization · Analysis of sensitivity · Decision support tool

1 Introduction

Due to its sustainability, Short Sea Shipping (SSS) has attracted a special attention as one of the most interesting truck hauls for intermodal chains (see Fig. 1). The search for alternatives to road congestion has boosted transport policies based on the idea of intermodality as a sustainable solution for 'door-to-door' transport. Proof of this explicit support is the evolution of the SSS concept from 2001 towards motorways of the sea (MoS). In the European Union, it is defines as: SSS services along with the intermodal services and the ports that are affected by the establishment of the intermodal chains (White Paper: European Transport Policy for 2010). Furthermore, Canada and the United States signed a *Memorandum of Cooperation on Sharing Short Sea Shipping Information and Experience* in 2003 [1].

The SSS concept integrated into intermodal chains (MoS) has been widely studied across different economic regions over the last decade and from different perspectives: in South America [2], Brooks, Mary and Wilmsmeier [3], North America [4], Australia [5], Asia [6, 7], among others. Consequently, far from being a regional term, MoS are currently an offshore concept and have been widely studied.

Despite this political support, a broad consensus exists about the limited success of this transport alternative [8]. Among others, the following reasons have been highlighted by most researchers: An imbalance in financing among transport modes; despite the political support for intermodality, significant public funds are invested in roads and railway infrastructures [9, 10] and this 'harms' the intermodal chains through SSS, especially, when the external costs have not been totally internalized by road transport [11]. Second, most previous studies have identified the suitable maritime routes to articulate to intermodal chains by assuming that the technical and operative features of fleets are fixed. Most relate to Ro–Ro vessels with previous activity on other maritime routes. As a result, many studies have ended up by adapting the maritime routes to the current fleets instead of adapting the fleets to the most efficient and effective routes. Finally, the rapid normative development in land transport by demanding

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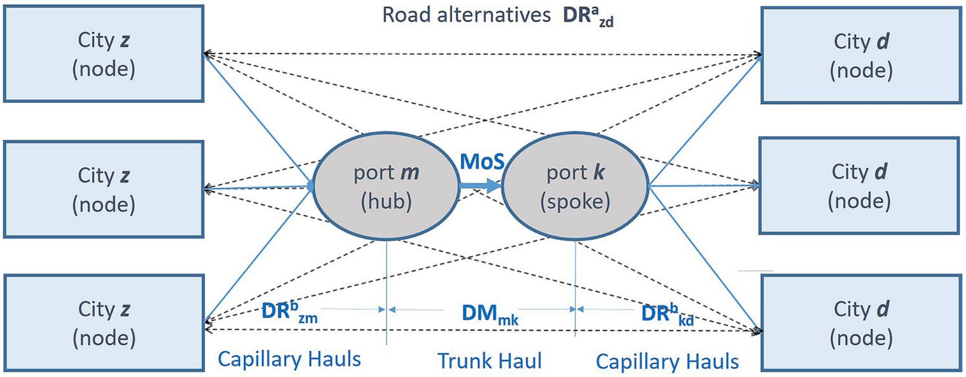

Fig. 1 'Many to Many' transport network

higher pollutant restrictions in comparison to a very slow maritime normative in terms of sustainability [12] along with the low impact of economies of scale in SSS with small and quick vessels [13, 14] has led to intermodal chains not being as sustainable as was thought in the past [7, 15].

Even though the articulation of successful intermodal chains is of general interest, private companies make the decisions about the technical and operative features of the fleets and their operative localization, by determining the performance of the whole chain. However, as expected, they only focus on optimizing their activity on the haul on which they operate (see Fig. 1). This fact explains that, despite the vast potential Artificial Intelligence (AI) to offer global decision support tools and what-if analyses of intermodal competitiveness regarding other transport options, most studies in this domain have focused on just one haul (often on port operations or scheduling problems) through mono-objective formulations.

These partial approaches, combined with the simplification of the transport problems (see Fig. 1) to mono-objective formulations, have limited the exploration of intermodal competitiveness. Consequently, even though noteworthy findings exist in this field, very few publications have attempted to offer decision support tools based on a global perspective of 'door-to-door' transport. The research gap is apparent in the few published studies that use multi-objective models to analyze the joint effect of modifications to the features of the fleets and routes on intermodal performance.

This paper contributes to closing this research gap by introducing a multi-objective mathematical model to evaluate in terms of time, cost and environmental impact, and the competitiveness of 'many-to-many' intermodal chains with a seaborne haul [16], (see Fig. 1) in relation to trucking. This assessment, based on the competitiveness results of the whole transport network, permits us to reach global results, beyond seaborne, through the optimization of technical and operative features of the fleets and the geographical inputs of the routes at the same time. The mathematical model is the result of the integration of several models that were previously developed in the EU context [17, 18]. As a consequence of this, the model introduced here proposes feasible solutions in different frameworks, beyond the EU context, by overcoming a local approaching.

When the nodes of a particular transport network are known (possible origins or destinations of the freight on land), the resolution of the model provides the most suitable maritime route and its optimized fleet to establish an intermodal chain with the highest possibility of success against the road alternative (see Fig. 1). In addition, once the transport network with the most suitable maritime stretch has been determined, the sensitization of the model allows us to meet the most influent parameters on the results, therefore providing useful information for the various actors involved in the transport. Due to the complexity of the model (involving a multi-objective problem with linear and non-linear restrictions and continuous and variable parameters), a multi-objective genetic algorithm (NSGA-II) is used for its resolution.

Through the application to a real-life case: intermodal freight transport between the northern and the southern region with the V region (the central region) in Chile, the utility of the model is tested. The resolution of the model permits us not only to identify the most suitable MoS in Chile, between the hub port in the V region and the spoke ports (northern port—the North MoS; a southern port—the South MoS), but also to optimize the fleet operating on them. Hereafter, an analysis of scenarios in the model will indicate to vessel operators, policy makers, and heads of ports of the consequences of modifying variables on the expected performance of the intermodality.

This article is organized as follows. After the introduction, Sect. 2 briefly reviews the literature on optimization models applied to intermodal transport through SSS, and their resolution methods. Section 3 details the mathematical model and the assumptions on which it is based. The model is then applied to the real-life case of Chile in Sect. 4. The last section, Sect. 5, offers the main findings, global conclusions, and future research lines.

2 Literature review

The rapid development of the heuristics and metaheuristics for the resolution of complex realistic mathematical models has made it possible to handle conflicting objectives simultaneously. Indeed, maritime transport has taken advantage of the application of these algorithms to find optimal solutions regarding its characteristics, especially through mono-objective approaches, namely problems that handle multiple decision criteria but that are converted into a single-objective problem to simplify their resolution. Thus, authors like Dong and Song (2009), Wang and Meng [19], Kim et al. [20], and Chandra et al. [21] have used algorithms to determine the optimal sailing speed, fleet size, and chartered ship number under a number of restrictions (liner shipping network, transhipment, container routing, empty repositioning, inventory management in roll-on/roll-off shipping, etc.) through the optimization of mono-objective problems.

Despite the broad possibilities of analysis which are offered by Pareto frontiers (avoiding the inclusion of user preferences and, therefore, reducing the subjectivity [22]), very few authors in this research field have decided to address their study problem by employing a multi-objective model. Most have focused on the optimization of port operatives. Among them, the decision support tools developed by [23, 24] for container repositioning operations in a global liner shipping business (time and cost effectiveness) are noteworthy. In turn, Chen et al. [25] provided a decision support tool for managing truck arrivals at a container terminal through a bi-objective model that minimized both the truck waiting times and the truck arrival pattern change. Furthermore, the multi-objective model developed by Hu et al. [26] focused on the improvement of port activity. In this case, the port's operational cost and the vessel's fuel consumption were minimized to meet the impact of quay-crane allocation on the port's operational cost and the vessel's fuel consumption and emissions.

Focusing on the previous studies about the competitiveness of intermodality versus trucking, diverse assessment functions have been developed over the last decade. Thus, the problem has been tackled from different standpoints (environmental costs: [7, 27], total logistic costs: [6], monetary costs and travel times: [28], among others). From the literature review, it can be inferred that studies about intermodal transport based on the resolution of optimization models through heuristics are very scarce, especially when the development of multi-objective models and the analysis of Pareto fronts are taken into account.

Therefore, very few studies were identified from the search. Among them, two are notable due to their high capacities: the models published by Baykasoglu and Subulan [29] and Martínez-López et al. [17, 18, 30]. All of the aforementioned models tackle competitiveness between intermodality through MoS and trucking through multi-objective approaches. Baykasoglu and Subulan [29], for example, introduced a programming model for a multi-objective, multi-mode, and multi-period sustainable load planning problem. The model assesses the performance of the transport modes in terms of time, costs, and environmental impact, the latter being restricted to CO_2 emissions. Despite the fact that the model assumes Ro-Ro vessels' configuration to be a fixed parameter, it evaluates not only seaborne and road haulage but also the train option. Likewise, the work carried out by Martínez-López et al. [17, 18, 30] defined multi-objective models to evaluate the competitiveness of intermodality versus the road alternative for a particular MoS through the determination of an optimal fleet based on time, cost, and the most suitable kind of vessel (Ro–Ro or container vessel: [17]. The latter model was introduced with additional objective functions (external costs: [18] and additional capacities (the definition of the most suitable propulsion plant, fuels, and abatement systems: [30].

In light of the foregoing, multi-objective mathematical models for intermodality through MoS can be said to be still at an early stage. Accordingly, this paper attempts to broaden knowledge in this field through the resolution of a multi-objective model (the NSGA algorithm) that is introduced as a decision-making 'tool' for fleet and maritime route selection. This tool attempts to take advantage of the possibilities offered by genetic algorithms, not only by supporting compromise solutions (attending to different objectives at the same time) but also by visualizing the consequences of those decisions for the expected performance when the initial scenario changes (what-if analysis; [22]. These functionalities are the main contributions of this paper to the literature, since they permit the elaboration of medium-term strategies and, therefore, overcome the problems identified in the traditional approaches.

3 Mathematical model proposal

This section defines the mathematical model that is able to simulate the technical and operative characteristics of vessel fleets that operate in multimodal chains that include several seaborne hauls. This model is designed to be used in different geographical contexts; however, its application to a particular case requires us to outline the specific transport policies or particular requirements of the affected region. This latter point is addressed in the following paragraphs for the application case of Chile. From a mathematical point of view, the model integrates the following variables:

Transport networks: The 'many to many' model (with several capillary hauls on land, road stretches, and a trunk haul, sea leg, for the intermodal chains) is highly adaptable to most real ‘door to door’ haulages [16]. For this reason, this approach (see Fig. 1), has been mathematically defined for the generation of the routes in this work.

In the proposed model, each pair of ports: the ports of origin (M = {*1*,...,*m*), hub ports in the central region for the application case) and destination (K = {*1*,...,*k*} see Appendix A, spoke ports in the northern and southern regions in the application case) are capable of generating an MoS (the trunk haul, see Fig. 1) that is characterized by maritime distance ($\mathrm{DM}_{\mathrm{mk}}$; $\forall m \in \mathrm{M} \wedge \forall k \in \mathrm{K}$). For the application case, it is assumed that the spoke ports move all generated/delivered cargo in the region towards the hub port. Once the cargo arrives at the hub port, it is dispatched towards its final destination: the central or southern/northern regions of Chile or for exportation/importation (in these latter cases, the hub ports are nodes as well). The land origins (DD = *{1,...,d}*; possible nodes in the northern and southern hinterlands for the application case) and destinations of the multimodal chain (Z = *{1,...,z}*, see Appendix A; nodes in the central region) along with their probability of being selected as initial origin (X_d; $\forall d \in \mathrm{DD}$; Appendix A) and final destination ($X^c_{jz;}\forall z \in \mathrm{Z} \wedge \forall c \in \mathrm{ST} \wedge \forall j \in \mathrm{J}$; see Appendix A) have been conveniently integrated (see also Appendix A) in the transport network. In the application case, a probability distribution is assumed in relation to the population of the nodes (X_d; $\forall d \in \mathrm{DD}$). However, since the hub ports by themselves must be also considered as nodes in the central region, a fictitious population is assigned to the hub ports to reflect the external traffic and the cargo from the north with a final destination in the south (instead of the central region) and the opposite, beyond only receiving the load from/to the central region. Consequently, for the nodes in the central region, it is necessary to consider additional aspects of their probability distribution ($X^c_{jz;}\forall z \in \mathrm{Z} \wedge \forall c \in \mathrm{ST} \wedge \forall j \in \mathrm{J}$): the kind of MoS, North or South ($\mathrm{ST} = \{^c\}$, see Appendix A) and the direction of the transport (J = {*1*,...,*j*}).

Once the routes have been defined, they are characterized by the road distances between nodes and ports, capillary hauls ($\mathrm{DR}^{\mathrm{b}}_{\mathrm{zm}},$; $\forall z \in \mathrm{Z} \wedge \forall m \in \mathrm{M}$ and $\mathrm{DR}^{\mathrm{b}}_{\mathrm{kd}}$;$\forall k \in \mathrm{K} \wedge \forall d \in \mathrm{DD}$), and the road haulage distance ($\mathrm{DR}^{\mathrm{a}}_{\mathrm{zd}}$;;$\forall \mathrm{z} \in \mathrm{Z} \wedge \forall d \in \mathrm{DD}$) for the trucking option.

The vessel of the fleet and their operations: the model presented in this paper is only optimizing container vessels for MoS. To meet this aim, the model published by Martínez-López et al. [17] has been modified and tested for container vessels from 85 to 200 m in length between perpendiculars. The resolution of the model provides the technical and operative features of container vessels (Table 1) for its design in a conceptual step. Despite the numerous variables that are handled by the model, only five of them are non-dependent (the first five variables of Table 1).

Table 1 Main characterization variables of the fleet

VB	Speed of the vessel (Kn)
G_p: $\forall p \in \mathrm{PP}$	Cargo Capacity for the vessels (units)
MG_g; $\forall g \in \mathrm{GG}$	Cargo handling systems
$MM_{b;}$ $\forall b \in \mathrm{BB}$	Bow thruster installation
N_{trips}	Annual trips for the fleet
NB	Number of vessels
L	Length between perpendiculars (m)
B	Breadth (m)
D	Depth to the upper deck (m)
T	Summer draught (m)
FB	Freeboard (m)
GT	Gross tonnage (t)
∇	Buoyancy volume (m^3)
TPM	Deadweight (t)
PB	Propulsion Power (HP)
TME_{e}; $\forall e \in \mathrm{EE}$	Type of Main Engines
TP_{h}; $\forall h \in \mathrm{H}$	Type of propeller
NSL_{n}; $\forall n \in \mathrm{N}$	Number of shaft lines
NME_{i}; $\forall i \in \mathrm{I}$	Number of main engines

(see Appendix A for subscripts)

The default port operations in the model follow a ‘‘direct route’’ in the port [16]. This involves ideal conditions for the container movements in the port (minimum transit times for the containers in the port area). Obviously, these are adapted to the application cases.

The decision about this kind of vessel has been taken by considering the ‘good’ results obtained in an increasing number of studies focused on the operation of feeder vessels under SSS conditions [6, 7, 17, 27, 28]. In addition, the model is fully applicable to the real-life case,according to the data published by the System of Public Companies of Chile (SEP),[1] in 2014, the containerization rate of general cargo (external and domestic traffic) in a large number of Chilean ports reached and surpassed 70%.

Trucking vehicle: Since the suitable cargo units for transport through container vessels are TEUs and FEUs, a unitary weight is assumed for each one (Pp; $\forall \mathrm{p} \in \mathrm{PP}$): 12.5 and 20.5 t, respectively. Therefore, the trucks considered by the model must be able to transport containers (TEUs and FEUs) by taking into account their standard weight values (Table 2).

In terms of the application case, *The Economic Analysis of the Transport of National Cargo* published by the

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[1] Ministry of Transportation of Chile (https://www.sepchile.cl/documentacion/estadisticas-portuarias/?no_cache=1).

Table 2 Constraints for the mathematical model

RR1			$T < 10$
RR2			$FB > FBminimum$
RR3			$G_{p(final)} \geq G_{p\ (estimated)}$
RR4			$B \geq 13.56$
RR5	$D \geq$		7.15 if $PB \leq 33{,}794$
			$5 \times 10^{-4} \times PB - 5.52$ if $33{,}794 < PB \leq 53{,}600$
RR6			$4.94 < L/B < 7.50$
RR7			$1.55 < B/D < 2.31$
RR8			$7.85 < L/D < 14.17$
RR9			$2.35 < B/T < 3.20$
RR10			$672 \geq Ntrips \geq 384$
RR11			$VB < (3.7 \times \nabla^{0,1667}/0.514)$
RR12	$G_p \times Ntrips \geq$	MoS (North)	370,566; if $G_p = G_1$
			225,955; if $G_p = G_2$
		MoS (South)	791,408; if $G_p = G_1$
			482,566; if $G_p = G_2$
RR13	$(G_p/2) \times Ntrips \leq$	MOs (North)	276,973; if $G_p = G_1$
			168,886; if $G_p = G_2$
		MOs (South)	709,542; if $G_p = G_1$
			432,648; if $G_p = G_2$
RR14			$TVB \leq NB \times 12$

Undersecretary of Transport of the Government of Chile (2009) indicated that a suitable truck for intermodality in Chile is a vehicle with a maximum net weight of 25 tons (420 HP). The characteristics of this vehicle are equivalent to those that are classified as an "articulated vehicle" by the Directive 96/53/CE and as a category N_3 heavy-duty vehicle (HDV > 12Tn) by Directive 2007/46/CE of the European Parliament. Regarding the environmental technology of the vehicles, the National Institute of Statistics of Chile,[2] (2013) reveals that 76% of Chilean trucks were less than 10 years old. Consequently, the Euro-III technology (compulsory for trucks from 2000, Directive 98/69/EC) is assumed for the Chilean trucks (adopting a conservative approach).

3.1 Objective functions

In the following paragraphs, the objective equations (F1, F2, and F3) are introduced. Each has been formulated as a maximization of the advantage for intermodality against the trucking option (see Appendix A, as well). Thus, a higher value for the objective functions means a greater relative advantage for intermodality.

Objective 1: *Maximization of the advantage for intermodality in terms of transport costs (F1).*

Equation 1 (see Table 1 and Appendix A) illustrates the difference between the transport costs for unimodality (*CU*) and the intermodal chain (*CMU*). The latter, in turn, integrates the costs of capillary hauls (road stretches) and the trunk haul (maritime stretch, see Fig. 1).

The costs related to road transport (the unimodal option and the capillary hauls of the intermodal chain) include, besides the environmental costs (RE, RE_1, RE_2, see Appendix A): fuel, depreciation, financing costs, maintenance, repairs, personnel costs, and spare parts. All of these are incorporated into a unitary transport cost (€/km, see Appendix A): CK^d_p ($\forall p \in PP \wedge \forall d \in DIS$). This unitary cost along with the probability distributions for the cargo among the nodes (X_d; $\forall d \in DD$ and $X^c_{jz;} \forall z \in Z \wedge \forall c \in ST \wedge \forall j \in J$) and the distance of the legs (DR^a_{zd}, DR^b_{zm}, and DR^b_{kd}; see Fig. 1), are considered for the calculation of the road transport costs.

Likewise, the costs of the trunk haul (maritime stretch), aside from environmental costs (RE_3), include the necessary costs to obtain the minimum required freight. ($CT_c \forall c \in C$; see Appendix A): depreciation costs, financing costs, insurance costs, maintenance costs, crew costs, fuel costs, and

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[2] National Institute of Statistics of Chile. 2013. *Yearbook about Road Transport*. https://www.ine.cl/canales/chile_estadistico/estadisticas_economicas/transporte_y_comunicaciones/encuesta-estructural-transporte-carretera/2013/infografia_transporte_por_carretera_2015.pdf

port tariff costs (ship dues, cargo dues, pilot tariff, towing tariff, mooring dues, and loading/unloading costs):

$$F1=\max(\overbrace{RE+\left(\sum_{j=1}^{j}\sum_{z=1}^{z}\sum_{d=1}^{d}\left(X^{c}_{jz}\times X_{d}\times DR^{a}_{zd}\right)\right)\times(\frac{1}{2})\times\frac{CK^{d}_{p}}{P_{p}}}^{\textbf{CU}}\overbrace{\underbrace{-(RE_{1}+\left(\sum_{j=1}^{j}\sum_{z=1}^{z}\left(X^{c}_{jz}\times DR^{b}_{zm}\right)\right)\times(\frac{1}{2})\times\frac{CK^{d}_{p}}{P_{p}})-(RE_{2}+\left(\sum_{d=1}^{d}\left(X_{d}\times DR^{b}_{kd}\right)\right)\times\frac{CK^{d}_{p}}{P_{p}})}_{\textit{Capillary hauls}}\underbrace{-(RE_{3}+1/(G_{p}\times P_{p}\times N_{trips})\times\left(\sum_{c=1}^{12}(CT_{c})\right)))}_{\textit{Trunk haul}}}^{\textbf{CMU}}\tag{1}$$

Objective 2: *Maximization of the advantage for intermodality in terms of transport time (F2).*

Equation 2 (see Table 1 and Appendix A) collects the difference between the transport times invested by unimodality (*TVU*) and the intermodal chain (*TVM*). Like Eq. 1, the time invested by the intermodality integrates road times (capillary hauls) and maritime times (see Fig. 1).

Time invested in road transport (the unimodal option and the capillary hauls) collects the transit time and takes into account the national regulations. This comprises continuous transit times (speed–VT and distances, $DR^{a}{}_{zd}$, $DR^{b}{}_{zm}$, and $DR^{b}{}_{kd}$; see Fig. 1 and Eq. 2), compulsory resting times, the required time for changing drivers due to the maximum driving time allowed per day. For the application case, the Chilean normative for load driving establishes: the maximum permitted speed for a truck (*VT*) (Art. 145 of Law No. 18.290, Ministry of Transport and Telecommunications of the Government of Chile), 16 h of maximum driving time per day, for which two drivers are required ($\forall d\in\mathrm{DIS}$; see Appendix A), and a minimum resting time of 2 h per driver after five driving hours (Art. 25 bis of the Code of Work of the Government of Chile). Additionally, 1 h per day is assumed for changing drivers:

The time invested in the trunk haul (maritime stretch) involves: free sailing time, the time invested in port services (pilotage, towing, and mooring service- TS_{w}; $\forall w\in\mathrm{WW}$), and the loading and unloading times. Whereas the sailing time is calculated with the maritime distances ($DM_{mk}\forall m\in\mathrm{M}\wedge\forall k\in\mathrm{K}$) and the service speed of the vessels (*VB*), the loading and unloading times consider the cargo units of the vessel ($\mathrm{G}p$ $\forall p\in\mathrm{PP}$), the number of cranes for each port ($NC_{k;}\forall k\in\mathrm{K}$ and $NC_{m};\forall m\in\mathrm{M}$, see Appendix A) that simultaneously operate on a vessel, and their unitary cycles ($V_{k},\forall k\in\mathrm{K},V_{m},\forall m\in\mathrm{M}$).

Objective 3: *Maximization of the advantage for intermodality in terms of environmental costs (F3).*

Equation 3 (see Table 1 and Appendix A) collects the difference between the environmental costs for unimodality (*RE*) and the intermodal chain (*MUE*). The environmental costs of intermodality are made up of environmental costs of the capillary hauls and trunk hauls ($MUE=RE_{1}+RE_{2}+RE_{3}$; see Appendix A).

The introduction of Objective 3 ensures that sustainability will drive optimization with the same weighting factor as the other competitiveness attributes (times and costs, F1 and F2). This was not guaranteed with the inclusion of the environmental costs (RE, RE_{1}, RE_{2}, RE_{3}, see Eq. 1) in the

$$\begin{aligned}
&F2=\max((1/2)\times\sum_{j=1}^{j}\sum_{z=1}^{z}\sum_{d=1}^{d}(X^{c}_{jz}\times X_{d}\times[\left\lfloor\frac{\left\lfloor\frac{DR^{a}_{zd}}{16\times VT}\right\rfloor\times1+\frac{DR^{a}_{zd}}{VT}}{16}\right\rfloor\times24+\left[\left(\frac{\left\lfloor\frac{DR^{a}_{zd}}{16\times VT}\right\rfloor\times1+\frac{DR^{a}_{zd}}{VT}}{16}\right)-\left\lfloor\frac{\left\lfloor\frac{DR^{a}_{zd}}{16\times VT}\right\rfloor\times1+\frac{DR^{a}_{zd}}{VT}}{16}\right\rfloor\right]\times16])- && \textbf{TVU}\\
&-(1/2)\times\sum_{j=1}^{j}\sum_{z=1}^{z}(X^{c}_{jz}\times\left[\left\lfloor\frac{\left\lfloor\frac{DR^{b}_{zm}}{16\times VT}\right\rfloor\times1+\frac{DR^{b}_{zm}}{VT}}{16}\right\rfloor\times24+\left[\left(\frac{\left\lfloor\frac{DR^{b}_{zm}}{16\times VT}\right\rfloor\times1+\frac{DR^{b}_{zm}}{VT}}{16}\right)-\left\lfloor\frac{\left\lfloor\frac{DR^{b}_{zm}}{16\times VT}\right\rfloor\times1+\frac{DR^{b}_{zm}}{VT}}{16}\right\rfloor\right]\times16\right]))- && \textit{Capillary Hauls}\\
&-\sum_{d=1}^{d}(X_{d}\times\left[\left\lfloor\frac{\left\lfloor\frac{DR^{b}_{kd}}{16\times VT}\right\rfloor\times1+\frac{DR^{b}_{kd}}{VT}}{16}\right\rfloor\times24+\left[\left(\frac{\left\lfloor\frac{DR^{b}_{kd}}{16\times VT}\right\rfloor\times1+\frac{DR^{b}_{kd}}{VT}}{16}\right)-\left\lfloor\frac{\left\lfloor\frac{DR^{b}_{kd}}{16\times VT}\right\rfloor\times1+\frac{DR^{b}_{kd}}{VT}}{16}\right\rfloor\right]\times16\right])- && \textbf{TVM}\\
&-DM_{mk}/(VB\times1.85)-\sum_{w=1}^{w}TS_{w}-\frac{G_{p}}{NC_{k}\times V_{k}}-\frac{G_{p}}{NC_{m}\times V_{m}}) && \textit{Trunk Haul}
\end{aligned}\tag{2}$$

objective function of the overall costs (F1) due to their limited relevance within the overall transport costs:

$$\begin{aligned} F3 = \max\Bigg(& \frac{\sum_{u=1}^{u}\sum_{j=1}^{j}\sum_{z=1}^{z}\sum_{d=1}^{d}\left(X^{c}_{jz}\times X_{d}\times DR^{a}_{zd}\times FC_{p}\times 10^{-6}\times CF_{2u2}\times EGU_{u}\right)}{2\times P_{p}} - && \textbf{RE} \\ & -\frac{\sum_{u=1}^{u}\sum_{j=1}^{j}\sum_{z=1}^{z}(X^{c}_{jz}\times X_{z}\times DR^{b}_{zm}\times FC_{p}\times 10^{-6}\times CF_{2uv}\times EGU_{u})}{2\times P_{p}} - \frac{\sum_{u=1}^{u}\sum_{d=1}^{d}(X_{d}\times DR^{b}_{kd}\times FC_{p}\times 10^{-6}\times CF_{2uv}\times EGU_{u})}{P_{p}} - \quad (3) && \textit{Capillary Hauls} \\ & -\frac{1}{(G_{p}\times P_{p})}\times\Big(\sum_{u=1}^{u}(EG_{1u}\times DM_{mk}\times 0.54\times CF_{1u})+\sum_{u=1}^{u}(EG_{2u}\times TVB_{2}\times CF_{2uv})+\sum_{u=1}^{u}(EG_{3u}\times TVB_{3}\times CF_{3uv})\Big)\Bigg) && \textit{Trunk Haul} \end{aligned} \quad \textbf{MUE} \tag{3}$$

The environmental costs consider the following pollutants (U = {*1*,...,*u*}, see Annex A) for all transport modes: SO_2, NO_x, particles $PM_{2.5}$, and CO_2 (U = {*1*,...,*u*}). Likewise, the calculation method [18, 31] is also common for every transport mode: multiplication of the unitary costs for the pollutants (CF_{1u}, CF_{suv} $\forall s \in SS \wedge \forall u \in U \wedge \forall v \in V$; see Appendix A) and their emission coefficients (EG_{su}, EGU_u, $\forall s \in SS \wedge \forall u \in U$; see Appendix A).

However, whereas for road transport, the unitary costs of the pollutants [32, 33], and Jiang et al. 2014) are dependent on the population and the emission zone (V = {*1*,...,*v*}) (unimodality and capillary hauls); on the maritime haul, these unitary costs are dependent on the maritime stage: berthing, maneuvering, and free sailing (SS = {*1*,...,*s*}, see Appendix A).

In turn, the emission coefficient calculation for all pollutants follows the Tier I method [31] in road transport, while the emission coefficients for the vessels are calculated through the calculation sheet[3] developed by the Technical University of Denmark in collaboration with the Southern Denmark University [34, 35].

3.2 Constraints for the mathematical model

The model has several constraints that ensure the feasibility of the solutions obtained. Table 2 shows the constraints applied to the application case. Some of these are independent of the application case, but others must be adapted to the framework. The former relate to constraints on the dimensional limitations of a feeder vessel, whereas the latter are determined by the expected requirements for its activity.

The first group: constraints RR1–RR9 and RR11 ensure the technical feasibility of vessels (regardless of the application case): maximum draft (T), breath (B), minimum depth (D) in relation to the main propulsion power (PB), meeting of dimensional relationships (RR6–RR9) and international rules: RR2 is imposed to address the minimum freeboard (International Convention on load lines, 1966), and RR11 avoids the high-speed craft condition (High Speed Craft Code, MSC[4] 36(63) and Chapter X of Safety of Life at Sea—SOLAS). In turn, the second group is made up of RR10, RR12, RR13, and RR14 (see Table 2). These are dependent on the application case; they force the overall cargo capacity of the proposed fleet along with its activity to satisfy the current transport demand for the container load. The values shown in Table 2 for these restrictions have been taken from the activity requirements demanded by the Chilean authorities (Sect. 4.1).

3.3 Resolution of the model

The parameters shown in Table 1 are the NSGA-II population´s chromosomes. During the evolution process, the genes take values between -1 and 1. This is required by JEAF, which is the EA framework employed in this work [36].

Using the configuration parameters shown in Table 3, a population of possible solutions has been reached for every iteration. The solutions are evaluated in according to the objective functions and the iteration process [continue up to meet the maximum number of calls to the evaluation function: 10,000 *n* (being *n* the problem dimension, this is the number of optimization variables, see Table 1). In every iteration, 50 independent tests were executed. The tests were compared through hyper volume [37]. This allows us to compare several executions from an algorithm by considering the Pareto fronts obtained through a unique value, when the hyper volume of the Pareto fronts is higher, the quality of the results is higher as well.

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

[4] Maritime Safety Committee.

Table 3 Configuration parameters for NSGA-II

Operator	Parameters	Values
Tournament Selection	Pool size	2
SBX-crossover	Probability	5%
Polynomial Mutation	Probability	60%
	N	1

4 Application to Chile's reality

As a consequence of the widening of the Panama Canal, Chile expects an increase in the size of vessels that arrives at its coasts and, consequently, an enlargement of their ports. With the aim of optimizing its resources, Chile is evaluating the possibility of investing in a single hub port in the central region of the country (the V region; Valparaíso or S. Antonio). Thus, Chile would channel the main external traffic of the country through this hub port, and due to its geographical particularities, the internal traffic would be connected from the north and south regions with the central region through MoS.

This case is especially interesting from an optimization standpoint due to the imbalance of the external and domestic traffic flow among regions (see Table 4 from Ministry of Transport and Telecommunications of Chile and Ports—DIRECTEMAR, 2012[5]). Despite this, the overall cargo volume (see Table 4) that is moved in both regions (4,632,071 t in the north and 9,892,605 t in the south) largely exceeds the minimum volume recommended (minimum yearly movement of 1,530,000 t; bilateral a possible spoke ports for agreement between France and Spain to articulate MoS on their Atlantic coasts—BOE No. 92, 2006) to ensure the social benefits with the establishment of MoS.

Figure 2 shows the extreme nodes (rectangles) of the intermodal chains for the three regions: north, south (DD = {*1,...,d*}; see Appendix A), and central (Z = {*1,...,z*}); these are: two nodes in the northern and southern regions (blue rectangles) and five nodes in the central region (grey rectangles). Aside from the hub ports (M = {*1,...,m*}), which are underlined, Fig. 2 shows the possible spoke ports for the MoS North and South (K = {*1,...,k*}; see Appendix A).

Additionally, the following assumptions have been taken into account for the resolution of the application case; once the specific type of vehicle has been selected for the road transport (see Sect. 3), the unitary costs (CK^{d}_{p}, $\forall p \in PP \wedge \forall d \in DIS$) are taken from the information published by the Under Secretary of Transport of the Government of Chile (2011 updated to 2015).[6] Furthermore, for the costs related to the seaborne stretch, see Eq. 1), the following engines are assumed for the optimization of the fleets: a medium-speed and two-tier engine operating with marine diesel oil (MDO) as the fuel type (therefore, any abatement systems are not considered in this analysis). This assumption also influences the value of the emission coefficients EG_{su} ($\forall s \in SS \wedge \forall u \in U$) for the trunk haul (see Eq. 3). Finally, owing to the lack of information about the unitary costs for the pollutants in Chile (CF_{suv}, $\forall s \in SS \wedge \forall u \in U \wedge \forall v \in V$), the values published for Portugal [33] are taken as a reference, because the calculation models for the unitary costs take into account the population densities, meteorological conditions, and traffic patterns in the countries (the distribution of exhaust emissions), which are all very closely related to the economic development.

The analysis will be carried out in three steps:

Preliminary scenarios: The competitiveness of the intermodal chains articulated through all possible MoS in the north and in the south will be evaluated by assuming identical conditions (standard values for the port variables). In such a way, the spoke ports will be evaluated by considering only the competitiveness offered by their geographical location.

Current scenarios: From the previous selection of MoS, a new evaluation of the competitiveness of intermodal chains is carried out but considering particular conditions (real port values) for every port analyzed.

Analysis of sensitivity: The modification of the initial variables will lead to new scenarios. The new frameworks will permit the simulation of the performance and ruggedness of the intermodal chains when the initial scenario changes.

4.1 Preliminary scenarios

The analysis undertaken in this section attempts to determine the most efficient and effective spoke ports in the northern and southern regions to establish MoS with the V region. This assessment is based on geographic criteria in such a way that the analysis uniquely quantifies the performance of the intermodal chains with common extreme points in all cases (DD = {*1,...,d*} and (Z = {*1,...,z*}; see Appendix A and Fig. 2) but with different locations for their cargo consolidation centres (spoke ports (K = {*1,...,k*}). Thus, by means of assuming the same port costs and number, and the same characteristics of the port facilities (see Appendix B), the

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[5] DIRECTEMAR (2012); Ministry of Transport and Telecommunications of Chile and Ports (https://web.directemar.cl/estadisticas/puertos/default.htm).

[6] Under Secretary of Transport, Ministry of Transport and Telecommunications of the Government of Chile. 2011. *Analysis of the Costs and Competitiveness of the Modes of Inter-urban Land Transport* (2011). https://www.subtrans.cl/subtrans/doc/Informefinalcorregido.pdf

Table 4 Yearly transport needs for MoS per direction

Ports of North Region	North–South & Centre (exports and cabotage) (t)	South & Centre–North (imports and cabotage) (t)
Arica	124,835	147,394
Iquique	412,948	75,311
Mejillones	122,186	121,964
Angamos	1,576,985	570,598
Antofagasta	1,225,215	254,636
North Total	**3,462,168**	**1,169,903**
Ports of South Region	**North & Centre–South (imports and cabotage) (t)**	**South–North & Centre (exports and cabotage) (t)**
Lirquen	62,576	3,144,777
San Vicente	657,911	3,612,814
Coronel	302,832	2,111,696
South Total	**1,023,319**	**8,869,287**

Source: DIRECTEMAR, 2012

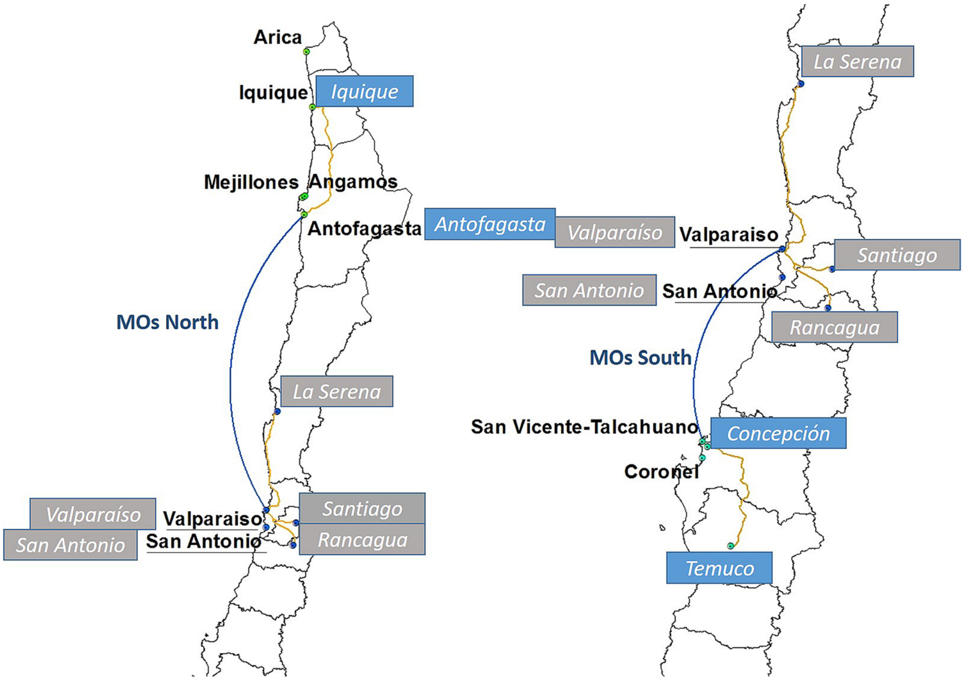


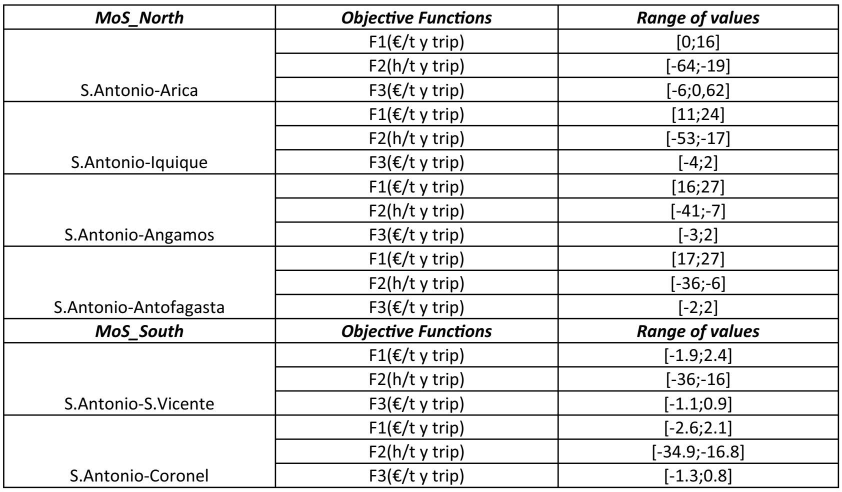
Fig. 2 Extreme nodes and possible hub and spoke ports for the MoS

intermodal chains articulated through different ports will be evaluated under identical conditions. Furthermore, the assessment considers the ideal conditions for the port operations in all ports: a direct route for containers in the port [16] and vessels being exempted from pilotage and towing use if they have a bow thruster. Finally, the analysis is carried out for only one hub port (S. Antonio), because the results for the two hub ports will be similar because of their geographical proximity ($M = \{1,...,m\}$ Valparaíso and S. Antonio; see Fig. 2).

The competitiveness results obtained from the optimization are shown in Table 5. In parallel, the optimized fleets able to provide these results have the following ranges of cargo capacity, speed, and length: for the MoS North, fleets are made up of vessels with $620 \le \text{TEUs} \le 1060$, $15 \le \text{VB} \le 25$ knots and $117 \le L \le 140$ m. In turn, for the MoS South, the optimized fleets are: $1180 \le \text{TEUs} \le 1500$, $15 \le \text{VB} \le 30$ knots, and $150 \le L \le 160$ m.

The results obtained show negative values for time (F2) in all the cases for the MoS North (see Table 5). This involves penalization for intermodality, which reaches the minimum disadvantage through the S. Antonio–Antofagasta MoS (6 h/t and trip; see F2 = (– 6) in Table 5). Opposite to this, the competitiveness of intermodality through the optimized fleets is positive in terms of the total costs (F1) in all cases for MoS North (see Table 5). Again, the highest value is offered by the S. Antonio–Antofagasta MoS (F1 = 27€/t and trip; see Table 5), albeit very close to the results offered by S. Antonio–Angamos (see Table 5). Regarding MoS South (see Table 5), the advantage in terms of costs (F1) for intermodality is much less and the disadvantage in terms of time (F2) is considerable in all cases. In addition, the difference in the performance of the intermodal chains through candidate ports in the south (S. Vicente and Coronel) is very slight.

Table 5 Range of results for the simulations of the MoS operating with optimized fleets in preliminary scenarios



MoS_North	***Objective Functions***	***Range of values***
S.Antonio-Arica	F1(€/t y trip)	[0;16]
	F2(h/t y trip)	[-64;-19]
	F3(€/t y trip)	[-6;0,62]
S.Antonio-Iquique	F1(€/t y trip)	[11;24]
	F2(h/t y trip)	[-53;-17]
	F3(€/t y trip)	[-4;2]
S.Antonio-Angamos	F1(€/t y trip)	[16;27]
	F2(h/t y trip)	[-41;-7]
	F3(€/t y trip)	[-3;2]
S.Antonio-Antofagasta	F1(€/t y trip)	[17;27]
	F2(h/t y trip)	[-36;-6]
	F3(€/t y trip)	[-2;2]
MoS_South	***Objective Functions***	***Range of values***
S.Antonio-S.Vicente	F1(€/t y trip)	[-1.9;2.4]
	F2(h/t y trip)	[-36;-16]
	F3(€/t y trip)	[-1.1;0.9]
S.Antonio-Coronel	F1(€/t y trip)	[-2.6;2.1]
	F2(h/t y trip)	[-34.9;-16.8]
	F3(€/t y trip)	[-1.3;0.8]

Due to the very close results obtained through Angamos and Antofagasta in the MoS North and S. Vicente and Coronel in the MoS South (see Table 5), the characteristics of the optimized fleets will be analyzed for every case to support the decision-making process relating to spoke ports. Table 6 shows fleet solutions with intermediate results in time (F2) and costs (F1) for the MoS North (inside the range values obtained from the optimization, see Table 5) and the maximization of the competitiveness in terms of costs (F1) for the MoS South.

According to Table 6, intermodality through Antofagasta has two advantages over Angamos: there is greater competitiveness in terms of time (over five hours) and the necessary fleet needs less vessels (four versus five). However, the comparison between S. Vicente and Coronel does not show such a clear difference. Even though there is a slight advantage for the intermodal chains through S. Vicente, this is insufficient to choose the MoS South.

Finally, the high dependence on the environmental results (F3), regarding not only the characteristics of the

Table 6 Solutions of optimized fleets for the MoS in the preliminary scenarios though S. Antonio

Fleets	Angamos	Antofagasta	San Vicente	Coronel
Cargo units	FEUs	FEUs	FEUs	FEUs
Cargo capacity (G_p)	761 TEUs	608 TEUs	1,334 TEUs	1,330 TEUs
Speed of the vessels (Kn)	17.26	16.90	16.11	16.58
Bow thruster	Yes (MM_2)	Yes (MM_2)	Yes (MM_2)	Yes (MM_2)
Cargo handling systems	Port cranes (MG_2)	Port cranes (MG_2)	Port cranes (MG_2)	Port cranes (MG_2)
Number of vessels (NB)	5	4	3	3
Yearly trips (N)	668	670	672	672
L (m)	127.56	118.49	158.2	157.8
B (m)	21.45	20.15	27.41	27.34
D (m)	10.55	9.85	13.32	13.27
GT (Ton)	8.231	6.798	16.612	16.268
Propeller	Conventional screw (TP_1)	Conventional screw (TP_1)	Conventional screw (TP_1)	Conventional screw (TP_1)
Number of shaft lines	1 (NSL_1)	1 (NSL_1)	1 (NSL_1)	1 (NSL_1)
Main engine	Diesel (TME_1)	Diesel (TME_1)	Diesel (TME_1)	Diesel (TME_1)
Number of main engines	1 (NME_1)	1 (NME_1)	1 (NME_1)	1 (NME_1)
Results				
F1(€/(t × trip))	25.80	25.41	1.85	1.50
F2(h/(t × trip))	− 27.58	− 22.73	− 30.75	− 31.36
F3(€/(t × trip)	1.02	1.04	0.46	0.37

fleets, but also those of the maritime route, is very notable. Thus, whereas the sustainability of intermodality is ensured through Antofagasta (600 nautical miles) when the speed of the vessels is lower than 24 kn, through southern ports (at an average of 210 nautical miles), the speed of the vessels must be lower than 20 kn.

4.2 Current scenarios

In this section, the intermodal chains, which were selected in the previous section, will be simulated again but under current conditions; that is, taking into account the particular values of efficiency and costs of the port services involved (CT_7, CT_8, CT_9, CT_{10}, CT_{11} and CT_{12}, see Appendix B and Eq. 4). These new simulations will permit us to meet the real performance of the transport networks in the Southern region and consequently to take a decision about the most convenient spoke port in the South (S. Vicente or Coronel). In turn, the new simulations will allow as well, to know the competitiveness of the transport networks through the possible hub ports (Valparaíso or S. Antonio):

$$CMUtrunk\_haul = RE_3 + \frac{1}{(Gp \times Pp \times Ntrips)} \times \left(\sum_{c=1}^{12} (CT_c) \right). \tag{4}$$

Thus, the current scenario simulations, the costs of the seaborne stretch (see expression 4) in the first objective function (F1; see Eq. 1) are calculated by considering the current values for the port dues and services—ship dues (CT_7), load dues (CT_8), pilotage dues (CT_9), towing charges (CT_{10}), mooring dues (CT_{11}), and loading/unloading dues (CT_{12}). Thus, the pilotage dues (CT_9) are estimated by taking into account the rules of the Chilean Government, first articles 20 and 21 of the *Regulation of Pilotage* (4th edition, 2015, published by the Directorate General of Maritime Territory and Merchant Shipping) about free maneuvers of pilotage, and afterwards the globalized tariff of *Regulation of Tariffs and Rights* (2015, article 301, Chapter III), published by the Directorate General of Maritime Territory and Merchant Shipping. The towing charges (CT_{10}) are calculated by applying the harbour master's office orders related to every port analyzed about the compulsory use of the towing service. The values of those tariffs were taken from Saam[7] company (the charges from different private companies are very close to each other and are similar for all the ports evaluated). Finally, the remaining port dues are taken from the annexes for the tariffs of 2016 of the Service Handbooks (South Pacific Terminal Valparaíso—TPS, International Terminal Antonio—STI, International Terminal Antofagasta ATI, and International Terminal of Vicente—SVTI).

Turning to the updated values regarding the preliminary scenarios (see Appendix B), the ship dues and the loading/unloading tariffs prove to be lower in the preliminary scenario, whereas the load dues are higher than those for the current scenario. With regard to the candidate ports for the hub (Valparaiso and S. Antonio), their port dues are very close; in fact, only the loading/unloading tariff is slightly higher for Valparaiso. Consequently, the expected results for intermodality through the two ports are similar in terms of costs; consequently, the optimized fleets to articulate the MoS are similar, as well:

$$TVMtrunk - haul = \sum_{w=1}^{w} TSw + \frac{Gp}{NCk \times Vk} + \frac{Gp}{NCm \times Vm}. \tag{5}$$

Likewise, in the current scenario simulation, the time invested in the trunk haul (see expression 5) for the calculation of the second objective function (F2; see Eq. 2) must be updated with real values for every port. However, even though the maximum number of cranes able to operate in a vessel for every port (NC_k $\forall k \in$ K and $NC_m \forall m \in$ M) and their speeds (V_k $\forall k \in$ K and V_m $\forall m \in$ M) are available for the ports analyzed in this application case (see Appendix B), there is a significant lack of information about the time invested in port operations (TS_w, $\forall w \in$ WW; see Appendix A). As a consequence of this, the standard values used for this domain in the preliminary scenarios were assumed.

In this regard, the limitation of the cargo-handling systems for the current scenario regarding preliminary scenarios (see Appendix B) suggests penalization of the results in terms of time for these simulations in current scenarios in comparison with the preliminary scenarios.

Figures 3 and 4 show the results obtained in the current scenarios (Pareto fronts) from the simulations of the possible MoS North from Antofagasta (with S. Antonio or Valparaiso) and MoS South from S. Vicente. Each circle represents a fleet solution for the MoS analyzed. Thus, the fleet solutions located at the left upper extreme maximize the F2 value (competitiveness in terms of time). This involves fleets of quick vessels (significant service speeds and, therefore, high required power and emission coefficients) with little cargo capacity to minimize the loading/unloading time in the port. As a consequence, the effects of economies of scale are small and these fleet solutions penalize the competitiveness of the intermodality in terms of the overall costs (F1) and environmental costs (F3). On the opposite side (the lower right extreme; see Figs. 3 and 4), the solutions that prioritize competitiveness in terms of costs (F1) offer better results in terms of the environmental impact (F3), because they are fleets with large and slow

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[7] https://www.saam.com/en/

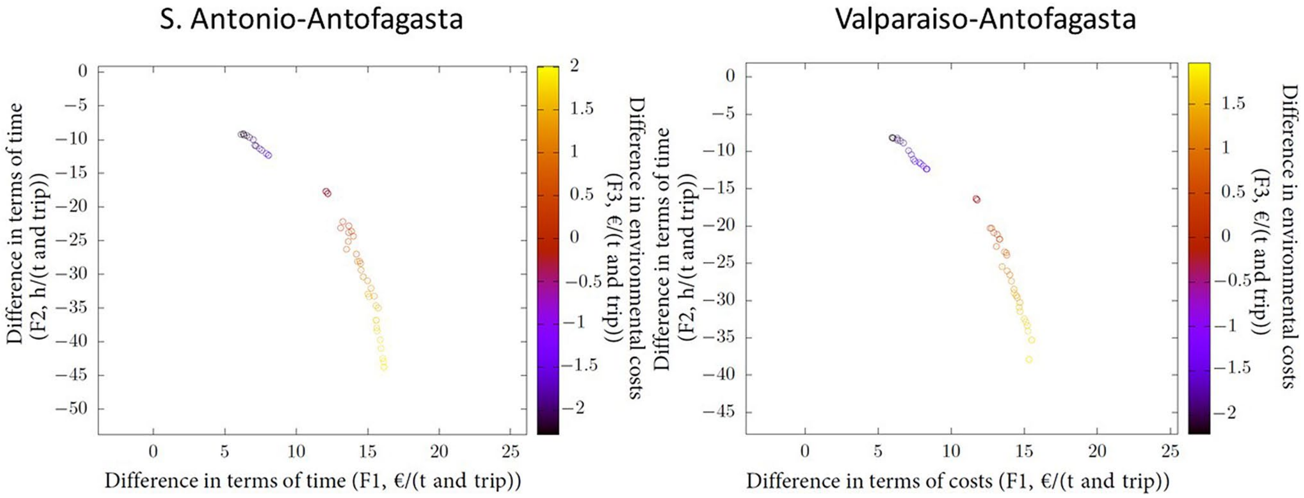

Fig. 3 Pareto fronts for intermodal chains articulated through Antofagasta for the MoS North

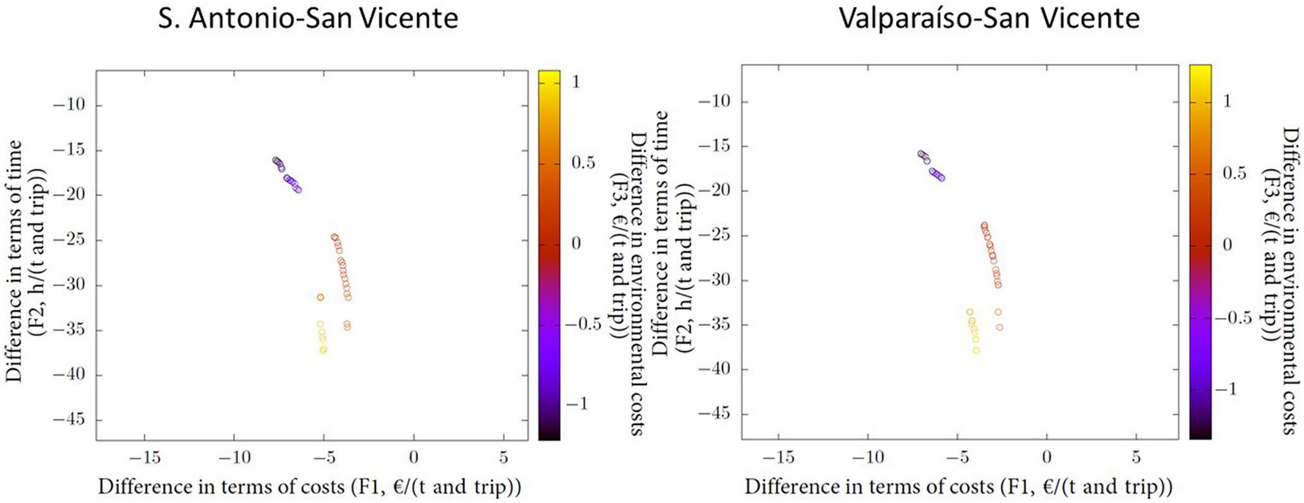

Fig. 4 Pareto fronts for intermodal chains articulated through San Vicente for the MoS South

vessels; however, they also produce long transit times for the chains (F2).

Table 7 shows the results of competitiveness for intermodality by considering the optimized fleets that have been taken (from Pareto fronts) by following the same selection criteria as in the previous scenarios: the intermediate solutions for F1 and F2 values in MoS North and the solutions that maximize competitiveness in costs for MoS South.

The optimized fleets for current scenarios are very similar for the MoS through both candidate hub ports (Valparaíso and Antonio, see Table 7): for MoS North, the results are $578 \leq \text{TEUs} \leq 1000$, $15 \leq \text{VB} \leq 30$ kn, and $117 \leq \text{L} \leq 140$ m, and for MoS South, they are $1199 \leq \text{TEUs} \leq 1589$, $15 \leq \text{VB} \leq 30$ kn, and $156 \leq \text{L} \leq 161$ m. In turn, the fleets obtained are close to those reached in the preliminary scenarios from S. Antonio (see Tables 6 and 7). These results suggest a certain independence of the optimized fleets for the MoS from moderate changes in the port conditions.

However, the results change significantly with the modification of the port conditions (a relevant disadvantage exists in costs (F1) and time (F2) in the current scenarios with regard to the preliminary scenarios). There remains an advantage in costs (average 13€/t and trip; see Table 7) for intermodality through MoS North. This competitiveness might be sufficient to balance the time penalty (21 or 22 h more than trucking, which takes 26.5 h) offered by intermodality for the transport of some kinds of non-perishable goods. Unlike the MoS North, intermodality through MoS

Table 7 Solutions of optimized fleets for the MoS in the preliminary scenarios

Spoke Port(k)	Antofagasta		S. Vicente		Coronel	
hub port (m)	Valparaiso	San Antonio	Valparaiso	San Antonio	Valparaiso	San Antonio
Cargo units	FEUs	FEUs	FEUs	FEUs	FEUs	FEUs
Cargo capacity (G_p)	579 TEUs	583 TEUs	1312 TEUs	1311 TEUs	1302 TEUs	1302 TEUs
Speed of the vessels (Kn)	18	18	19.00	19.33	20.8	21.0
Bow thruster	Yes (MM_2)	Yes (MM_2)	Yes (MM_2)	Yes (MM_2)	Yes (MM_2)	Yes (MM_2)
Cargo handling systems	Port cranes (MG_2)	Port cranes (MG_2)	Port cranes (MG_2)	Port cranes (MG_2)	Port cranes (MG_2)	Port cranes (MG_2)
Number of vessels (NB)	4	4	3	3	3	3
Yearly trips (N)	669	671	670	671	672	672
L (m)	118.36	119.23	158.00	158.00	158.00	158.32
B (m)	20.13	20.25	27.36	27.38	27.38	27.43
D (m)	9.84	9.90	13.29	13.31	13.30	13.33
GT (ton)	6.658	6.746	15.283	15.251	14.809	14.836
Propeller	Conventional screw (TP_1)	Conventional screw (TP_1)	Conventional screw (TP_1)	Conventional screw (TP_1)	Conventional screw (TP_1)	Conventional screw (TP_1)
Number of shaft lines	1 (NSL_1)	1 (NSL_1)	1 (NSL_1)	1 (NSL_1)	1 (NSL_1)	1 (NSL_1)
Main engine	Diesel (TME_1)	Diesel (TME_1)	Diesel (TME_1)	Diesel (TME_1)	Diesel (TME_1)	Diesel (TME_1)
Number of main engines	1 (NME_1)	1 (NME_1)	1 (NME_1)	1 (NME_1)	1 (NME_1)	1 (NME_1)
Results						
F1(€/(t × trip))	12.92	13.26	− 3.23	− 4.24	− 3.61	− 4.66
F2(h/(t × trip))	− 21.00	− 22.17	− 25.68	− 25.41	− 26.77	− 26.20
F3(€/(t × trip)	0.87	0.71	0.33	0.26	0.07	0.02

South in the current scenarios is shown to be of little interest. Even though the simulations in the current scenarios provide a more advantageous position for S. Vicente than for Coronel to articulate the MoS in the south (almost 1 h; see Table 7), only the environmental results (F3) are favourable to intermodality in absolute terms against trucking (see Table 7). This loss of competitiveness proves to be critical for the feasibility of MoS South, for which articulating competitive intermodal chains (negative values for F1 and F2) through any spoke port (S. Vicente and Coronel) is not feasible. The main reason for this is the proximity of the spoke ports to the hub ports by land (average 600 km). This involves an average transit time by road of six hours for the transport network by truck, whereas the time invested in the intermodal chain reaches 32 h (an average of 26 h delay; see Table 7). This fact renders intermodality in the south unfeasible.

Finally, it is interesting to note that the simulations in the current scenarios are insufficiently conclusive to make a clear decision about the most suitable hub port in the V region to articulate the MoS. Although time is a critical attribute for intermodality, the time advantage offered by MoS North through Valparaiso (less than one hour; see Table 7) seems insufficient to cope with the higher cost penalization against S. Antonio.

4.3 Analysis of sensitivity

Even though the previous results were representative enough, they were achieved through simulations in static scenarios (fixed values for the inputs); which means that the results obtained are of limited applicability. To make the results more useful, this section analyzes the performance of intermodality when the initial scenario (base scenario) changes. To meet this aim, a sensitivity analysis is carried out on the model. This allows us to:

- Check the robustness of the initial results. This is, knowing whether the optimized fleet in the previous sections remains suitable within changing frameworks. In such a way, the risk assumed in decisions based on these results is minimized.
- Identify the influence of the main inputs of the framework on the competitiveness of intermodality. Thus,

policy makers, port authorities, and other transport stakeholders can more easily act on them.

The sensitivity analysis is carried out over the MoS North identified in the previous sections as the most suitable: Valparaíso–Antofagasta and S. Antonio–Antofagasta. The MoS south is not analyzed due to its lack of feasibility.

The analysis is undertaken by considering three groups of inputs with significant influence on the framework: the road inputs, port inputs, and demand. The first group includes the speed of the trucks (*VT)* and the unitary costs for the road (CK_{dp}; $\forall p \in PP \wedge \forall d \in DIS$); the inputs of the second group can be modified by the competent authority (port authorities, harbour master's offices, or private companies): port dues and service tariffs (CT_7–$CT_{12;}$ see Appendix A). Finally, demand is the cargo moved by the MoS annually.

In the analysis, the value of every variable will be modified in a 20% range over the base value (which is assumed in the current scenarios) with a positive and negative step of 10% (see Table 8).

4.4 Assessment of the influence of the road inputs

According to the Chilean normative on load driving (Art. 145 of the Law No. 18.290, Ministry of Transport and Telecommunications of the Government of Chile), the maximum permitted speed for a truck (*VT*) is 90 km/h (base value). In turn, the base value for the unitary cost of trucking (CK_{dp}, $\forall p \in PP \wedge \forall d \in DIS$) is taken from the information published by the Under Secretary of Transport of the Government of Chile (2011 updated to 2015) for Euro-III trucks (see Sect. 3). It is interesting to note that these unitary costs do not include the use of public facilities or any external taxes. In recent years, both concepts have been integrated by several authorities (Italian Eco-bonus, the Marco Polo Programme in the EU, etc.) to avoid public financing that implicitly supports unimodal transport against other transport solutions [8, 10, 11].

The results obtained from the simulations carried out though the modification of the road inputs can be seen in Fig. 5. As expected, whereas the influence of the speed of

Table 8 Assessment scenarios for the analysis of sensitivity

Scenario 1	Scenario 2	Scenario 3 = Current Scenario	Scenario 4	Scenario 5
120%Base value	110% Base Value	100%Base value	90% Base value	80% Base value

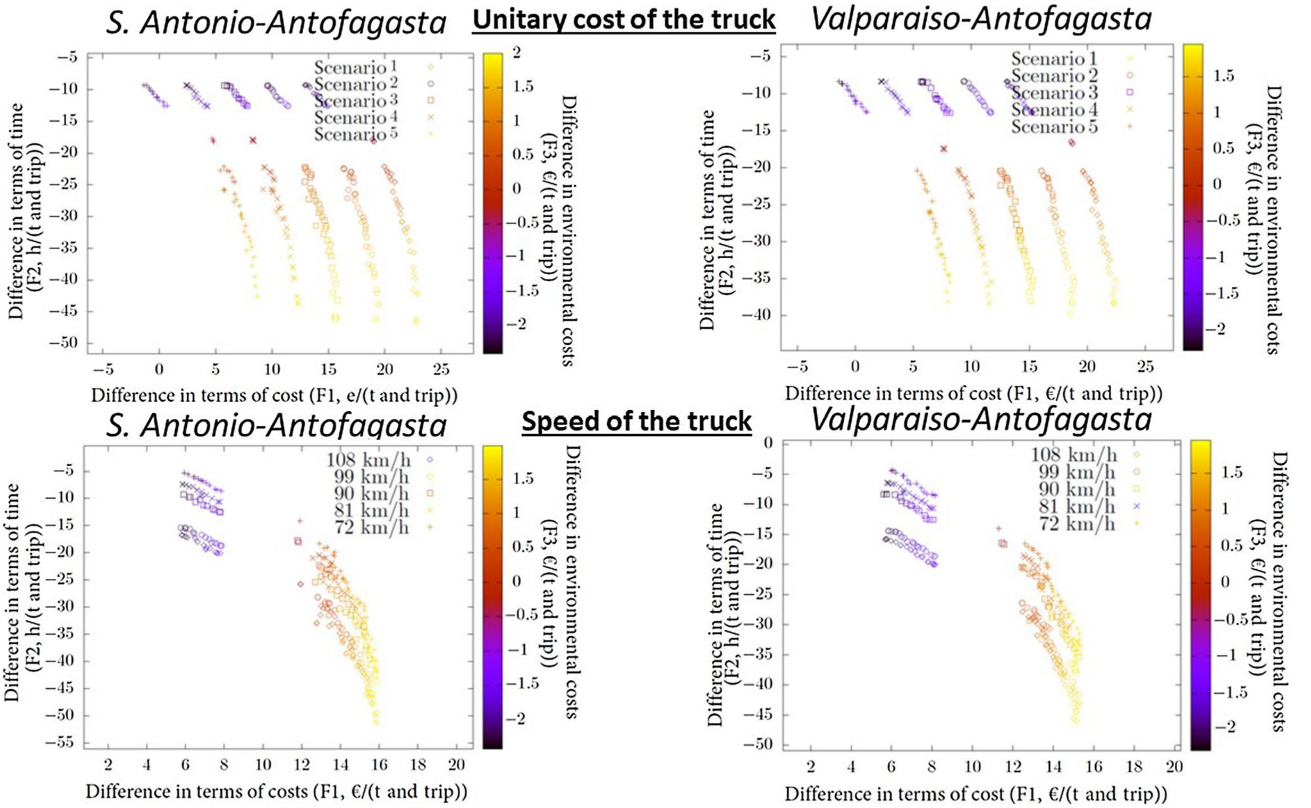

Fig. 5 Pareto fronts for intermodal chains articulated through MoS North when the road inputs are modified

the truck is mainly on the time invested in the transport (F2), the unitary cost by land influences the overall costs of the transport (F1).

The modifications of the unitary costs by road lead to a parallel displacement of the Pareto fronts on the abscissae axis; (see Fig. 5). That is, by means of increasing the unitary costs of trucking, the competitiveness of intermodality in terms of the costs (F1) constantly rises (every 10% increase in CK^{d}_{p} produces an average of 3.6 €/t and trip for the chains through MoS North; see Table 9).

Unlike the unitary costs by road, the performance of intermodality when the speed of the truck changes is not homogeneous for all intermodal chains (see Fig. 5). This is mainly due to the high dependence of its influence on the configuration of the transport network. Thus, whereas its increase seriously damages intermodality in terms of time when the transport net involves a long seaborne leg with short capillary hauls, competitiveness is less affected when the route is more balanced between sea and land haulage. In the latter case, the capillary hauls also take advantage of the increase in the speed of the trucks by moderating the damaging effects on intermodality. Consequently, intermodality through MoS North (with 19% of the whole distance on land and a reduction of 13% in the intermodal distance against the unimodal alternative) proves to be very sensitive to the speed of the trucks (see Fig. 5).

Table 9 shows the values achieved by the optimized fleet obtained in the simulations of the current scenarios (see Table 7) operating under the sensitivity scenarios (see Fig. 5). Focusing on this table, steps of 10% of the speed of the truck involve modifications of 1.8 h in the transit time for intermodality through MoS North, except when the change is from scenario 2 (99 km/h) to scenario 3 (90 km/h, base case). In the latter case, the modification involves six hours of difference, which is due to the step function for the calculation of the F2 value (See Eq. 2, adapted to the Chilean normative).

4.5 Assessment of the influence of the port inputs

These inputs include the facilities that are dependent on the ports, dues that are determined by the ports and dues that are determined by other entities.

Modifications in the number of available cranes in port, as expected, have a double impact: on the time invested in the port operations (F2) and on the total costs of intermodality through the variation on the costs by the ship due (CT_7; this charge is dependent on the port time). Furthermore, small vessels are more independent of the number of cranes, because their size does not permit many cranes to operate simultaneously. As can be seen in Fig. 6, operating with more cranes than those that are currently in Antofagasta does not generate a significant advantage (in scenarios 1 and 2, an average of three hours; see Table 10), the time penalty (F2) due to operating with a lower number of cranes (scenarios 4 and 5, reaching a delay of 19 h in relation to the current scenario) is worth highlighting.

The port dues, which are dependent on the port authorities: the ship dues (CT_7), load dues (CT_8), and loading/unloading dues (CT_{12}) are jointly modified for both ports of the maritime routes in every scenario. Their influence on the competitiveness of intermodality in terms of costs (F1) is relevant (see Fig. 6), and the behaviour is homogeneous. Thus, with every 10% modification of the port dues, the competitiveness of the chains will vary by an average of 1.75€/t and trip through MoS North (see Table 10). The results of this analysis contribute to the broader debate about the relevance of port tariffs to the success of SSS (e.g.[38].

Finally, the port dues, which are not dependent on the port authorities (pilotage—CT_9; towing services—CT_{10}) are also analyzed jointly. In this case, the impact of the modifications on the competitiveness of intermodality is very low in all cases by converging the simulations in a unique Pareto front.

4.6 Assessment of the influence of the demand.

The significant influence of the demand on the optimization of the fleets (constraints RR10, RR12, and RR13 of

Table 9 Sensitivity results of the intermodal chains through MoS North when the road inputs are modified

		Unitary Cost for trucking			Speed of the truck		
	Antofagasta	F1(€/t trip)	F2 (h/t trip)	F3 (€/t trip)	F1(€/t trip)	F2 (h/t trip)	F3 (€/t trip)
Valparaiso	Scenario1 (120%)	19.75	-20.85	0.82	12.80	-28.72	0.85
	Scenario2 (110%)	16.24	-21.07	0.85	12.70	-27.19	0.87
	Scenario3 (100%) Base Value	**12.92**	**-21.00**	**0.87**	**12.92**	**-21.00**	**0.87**
	Scenario4 (90%)	8.97	-20.56	0.80	12.52	-18.50	0.77
	Scenario5 (80%)	5.32	-20.38	0.78	12.61	-16.50	0.77
S. Antonio	Scenario1 (120%)	19.94	-22.12	0.68	12.99	-29.79	0.68
	Scenario2 (110%)	16.35	-22.42	0.68	12.83	-28.18	0.67
	Scenario3 (100%) Base Value	**13.26**	**-22.17**	**0.71**	**13.26**	**-22.17**	**0.71**
	Scenario4 (90%)	9.35	-22.22	0.68	12.89	-20.43	0.69
	Scenario5 (80%)	5.73	-22.14	0.68	12.91	-18.31	0.69

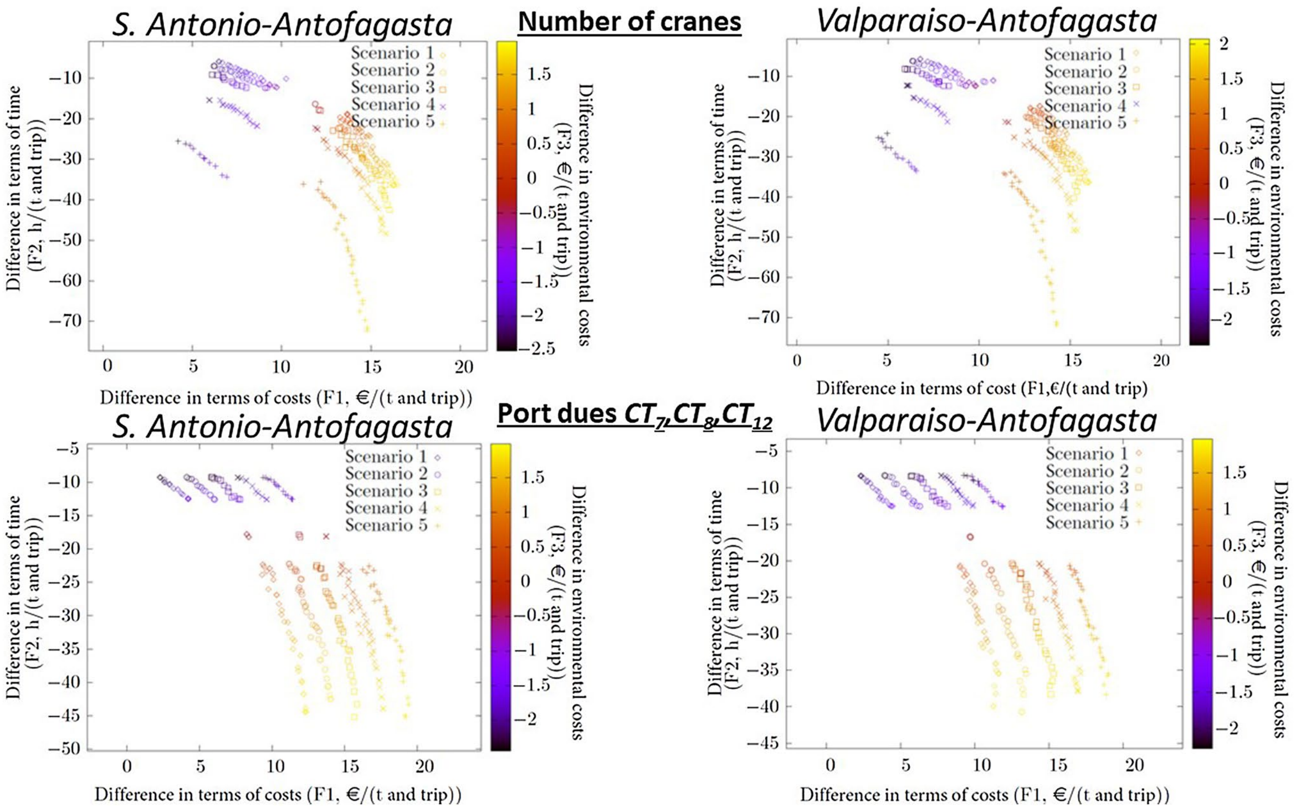

Fig. 6 Pareto fronts for intermodal chains articulated through MoS North when cranes and dues are modified

Table 10 Sensitivity results of the intermodal chains through MoS North when port inputs are modified

		Number of cranes			Port dues CT_7,CT_8,CT_{12}		
	Antofagasta	**F1(€/t trip)**	**F2 (h/t trip)**	**F3 (€/t trip)**	**F1(€/t trip)**	**F2 (h/t trip)**	**F3 (€/t trip)**
Valparaiso	Scenario1 (120%)	12.79	-17.74	0.82	9.28	-22.13	0.98
	Scenario2 (110%)	12.83	-18.94	0.85	10.66	-20.39	0.77
	Scenario3 (100%) Base Value	**12.92**	**-21.00**	**0.87**	**12.92**	**-21.00**	**0.87**
	Scenario4 (90%)	12.66	-23.62	0.78	14.47	-20.76	0.77
	Scenario5 (80%)	11.74	-33.76	0.70	16.59	-21.97	0.96
S. Antonio	Scenario1 (120%)	13.26	-19.66	0.74	9.42	-22.61	0.73
	Scenario2 (110%)	13.32	-20.68	0.70	11.26	-22.70	0.73
	Scenario3 (100%) Base Value	**13.26**	**-22.17**	**0.71**	**13.26**	**-22.17**	**0.71**
	Scenario4 (90%)	12.49	-25.69	0.73	14.75	-22.34	0.68
	Scenario5 (80%)	11.21	-36.15	0.71	16.23	-23.09	0.72

the model; see Table 2) along with the demand elasticities suggests the need for an analysis of whether the fleet initially chosen as the most suitable one will offer reasonable results if demand changes.

Owing to the initial imbalance in demand flow (see Table 4), the fleet must be able to cope with demand in both directions. Therefore, the optimized fleet from the current scenarios (see Table 7) for the MoS North has a greater cargo capacity per year than the required one in both directions (3% through Valparaiso and 5.4% through S. Antonio).

Figure 7 shows that the Pareto fronts are almost coincident when the demand changes by keeping the initial imbalance between both directions. This involves the optimal fleet operating under scenarios of analysis that are very close to those obtained from the current scenarios; therefore, the risk assumed with the initial optimized fleet would be low. However, the results of competitiveness

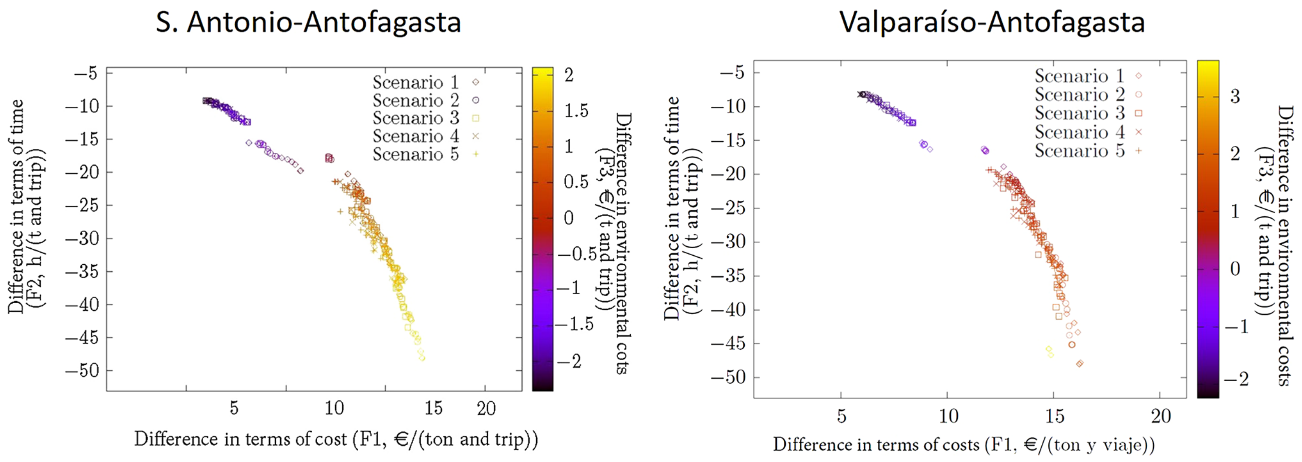

Fig. 7 Pareto fronts for intermodal chains articulated through MoS North when the demand is modified

Table 11 Sensitivity results of the intermodal chains through MoS North when the initial demand falls

		Demand		
	Antofagasta	**F1(€/t trip)**	**F2 (h/t trip)**	**F3 (€/t trip)**
Valparaiso	**Scenario3 (100%)** **Base Value**	**12.92**	**-21.00**	**0.87**
	Scenario4 (90%)	12.80	-20.69	0.85
	Scenario5 (80%)	12.56	-20.55	0.85
S. Antonio	**Scenario3 (100%)** **Base Value**	**13.26**	**-22.17**	**0.71**
	Scenario4 (90%)	13.05	-22.14	0.72
	Scenario5 (80%)	13.10	-22.01	0.71

if the demand falls would be slightly different (see Table 11).

5 Concluding remarks and discussion

This research introduces a multi-objective mathematical model able to assess the intermodal performance versus the unimodal alternative in different frameworks. The main singularity of this model is its capacity to identify optimized fleets along with the most suitable maritime routes to operate under MoS conditions by attending to the global competitiveness of whole chains. The multi-objective model permits an assessment to be made in terms of time, costs, and environmental costs. In this way, the analysis of solutions in the Pareto fronts permits to make decisions by considering all these attributes at the same time. In addition, the sensitivity analysis of the model enables different transport stakeholders to minimize the risk of making decisions.

The utility of the model was tested through its application to the Chilean case. Chile proves to be an interesting real-life case due to its geographical particularities (small shortening of the intermodal distance against the unimodal distance) and the consequences of the opening of the Panama Canal on its maritime traffic. In this application case, the model identified Antofagasta as being the most suitable port in the North region to articulate a MoS between the North and the Central region. Likewise, the resolution of the model identified for this MoS, a fleet comprising four container vessels of 580 TEUs at 18 knots of service speed as the most suitable to maximize the opportunities of success of the intermodal chains articulated through this seaborne haul. Even though intermodality through the MoS North has a notable disadvantage in terms of time in contrast with the road option, significant savings in total costs (13€/t and trip) and environmental costs (0.8 €/t and trip) make this intermodal chain feasible for non-perishable commodities. In turn, the resolution of the model advised against the establishment of a MoS between the central and Southern regions of the country.

Finally, the model has not found sufficient evidence to identify the most suitable hub port in the central region (Valparaíso or San Antonio) for the articulation of the MoS North. Despite this, the sensitization of the model has permitted us not only to provide further information about the Chilean case, but also to offer general findings for transport stakeholders. Thus, while moderate modifications in port conditions do not alter the suitability of fleets optimized for MoS under initial conditions, these modifications can have a relevant impact on the performance of the whole chain (every 10% of port dues would involve a modification of 1.75€/t and trip for intermodality in the Chilean case). Moreover, internalizing the external costs in trucking would have notable consequences on the competitiveness of intermodality (every modification of 10% of the unitary costs of road transport would produce €3.6/t and trip for the intermodality results in Chile). In conclusion, the port authorities and the policy makers have considerable room for maneuver regarding the competitiveness of intermodality. This fact is especially significant in the determination of the maximum permitted speed of the trucks, for which an increase from 90 km/h to 99kM/h would penalize intermodality by 6 h.

Further work will concern the definition of new specifications relative to port operation by integrating new port performance attributes into the mathematical model. In such a way, the new evaluations will consider additional criteria (e.g., pre-berthing time, real dwell time for containers, etc.), which have not been analyzed in the current model.

Appendix A

Subscripts

$\mathrm{A}=\{1,...,\mathrm{a}\}$: Different legs for the intermodal chains: capillary hauls (road haulage in both costs) and the trunk haul (maritime route).

$\mathrm{BB}=\{1,...,b\}$: Installation of bow thruster: yes or no.

$\mathrm{C}=\{1,...,c\}$: Cost inputs to reach the minimum required freight: depreciation costs, financing costs, insurance costs, maintenance costs, crew costs, fuel costs, and port tariff costs (ship dues, cargo dues, pilot tariff, towing tariff, mooring dues, and loading/unloading costs).

$\mathrm{DD}=\{1,...,d\}$: Final destinations on land (nodes). For the transport network of the application case, Iquique and Antofagasta are used in the northern region and Concepción and Temuco are used in the southern region.

$\mathrm{EE}=\{1,...,e\}$: Kind of main engines: diesel engines and turbines.

$\mathrm{GG}=\{1,...,g\}$: Cargo-handling systems: vessel cranes or port cranes.

$\mathrm{H}=\{1,...,h\}$: Possible propellers: screws or waterjets.

$\mathrm{I}=\{1,...,i\}$: Number of main engines.

$\mathrm{J}=\{1,...,j\}$: Direction for the transport (north–south and south–north).

$\mathrm{K}=\{1,...,k\}$: Possible spoke ports. For the application case, they are Arica, Iquique, Mejillones, and Antofagasta in the northern region and San Vicente and Coronel in the southern region.

$\mathrm{M}=\{1,...,m\}$: Possible hub ports. For the application case, they are Valparaíso and San Antonio in the V region.

$\mathrm{N}=\{1,...,n\}$: Number of shaft lines in the machine room.

$\mathrm{PP}=\{1,...,p\}$: Types of cargo units for container vessels: TEUs and FEUs.

$\mathrm{SS}=\{1,...,s\}$: Stages during maritime transport: free sailing, maneuvering (pilotage time, towing time, and mooring time), and berthing (loading and unloading operations).

$\mathrm{U}=\{1,...,u\}$: Group of evaluated pollutants: $\mathrm{SO_2}$, $\mathrm{NO_x}$, $\mathrm{PM_{2.5}}$, and $\mathrm{CO_2}$.

$\mathrm{V}=\{1,...,v\}$: Classification of the zones according to the harmful impact of the emissions: metropolitan zone and urban zone.

$\mathrm{WW}=\{1,...,w\}$: Port services for the maneuvering stage: pilotage, towing, and mooring services.

$\mathrm{Z}=\{1,...,z\}$: The origins on land (nodes). For the transport network of the application case, in the central region, Santiago, Valparaíso hub port (Valparaiso or San Antonio), La Serena, and Rancagua are used.

Superscripts.

$\mathrm{ST}=\{^{c}\}$: The MoS analyzed: MoS North and MoS South.

$\mathrm{DIS}=\{^{d}\}$: Compulsory driving with two drivers (yes and no).

Variables.

CF_{1u}: Unitary costs for the pollutants during free sailing (€/); $\forall u\in \mathrm{U}$.

CF_{suv}: Unitary costs for the pollutants considering the maritime stages and the affected zones (€/); $\forall s\in \mathrm{SS}\wedge \forall u\in \mathrm{U}\wedge \forall v\in \mathrm{V}$.

CT_{c}: Cost of the items for the maritime required freight of the trunk haul (€); $\forall c\in \mathrm{C}$.

CK^{d}_{p}: Unitary cost per kilometre by road (unimodal; the value is dependent on the required number of drivers and the cargo unit transported (€/km)); $\forall p\in \mathrm{PP}\wedge \forall d\in \mathrm{DIS}$.

CMU: Overall transport costs for the intermodal chain (€/(t × trip)).

CU: Overall transport costs for the unimodal alternative (€/(t × trip)).

DM_{mk}: Maritime distance for the trunk haul (km); $\forall m\in \mathrm{M}\wedge \forall k\in \mathrm{K}$.

DR^{a}_{zd}: Road distance for the unimodal alternative (km); $\forall z\in \mathrm{Z}\wedge \forall d\in \mathrm{DD}$.

DR^{b}_{zm}: Road distance for the capillary hauls in the intermodal chains from/to hub ports (km); $\forall z\in \mathrm{Z}\wedge \forall m\in \mathrm{M}$.

DR^{b}_{kd}: Road distance for the capillary hauls in the intermodal chains from/to spoke ports (km); $\forall k\in \mathrm{K}\wedge \forall d\in \mathrm{DD}$.

Table 12 Unitary port costs for the preliminary and current scenarios

		Preliminary scenarios	Current scenarios				
		For every port	Valparaíso	San Antonio	Antofagasta	S. Vicente	Coronel
Maximum Number of cranes/vessels (NCk and NC_m)	units	no limit	6	6	3	7	4
Average speed/crane (Vk and V_m)	(cycle/h)	27	27	27	18	18	22.5
Ship dues (CT_7)	(€/GT h)[9]	0.0167	1.536	1.574	1.954	2.618	2.772
Cargo dues (CT_8)	(€/TEU)	32.73	7.95	8.3	63.86	33.86	34.08
	(€/FEU)	49.104	13.04	13.61	104.72	55.53	55.9
Pilot dues (CT_9)	(€)[10]	231.28	112.68	112.68	112.68	112.68	112.68
	(€)	460.6	337.71	337.71	0	0	0
Towing dues (CT_{10})	(€/tug)	420.12	995.35	995.35	995.35	995.35	995.35
	(€/tug)	1093.42	2190.69	2190.69	2190.69	2190.69	2190.69
Mooring dues (CT_{11})	(€/mooring)[11]	96.35	0	0	0	0	390.87
	(€/mooring)	316.15	0	0	0	0	390.87
Loading/unloading dues (CT_{12})	(€/TEU)[12]	24.81	83.35	73.05	82.54	63.63	72.72
	(€/FEU)	49.61	124.98	109.56	128.9	98.16	90.90

EG_{su}: Emission coefficients for container vessels during the different maritime stages (kg/nm and in kg/h); $\forall s \in \mathrm{SS} \wedge \forall u \in \mathrm{U}$.

EGU_u: Emission coefficients for trucking (gr of pollutant/kg of fuel consumed); $\forall u \in \mathrm{U}$.

FC_p: Fuel consumption for trucks by considering the cargo unit transported (gr fuel/km); $\forall p \in \mathrm{PP}$.

CN_k: Number of cranes per vessel $\forall k \in \mathrm{K}$.

CN_m: Number of cranes per vessel $\forall m \in \mathrm{M}$.

MUE: Environmental costs for the intermodal chains (€/(t × trip)).

RE: Environmental costs (€/(t × trip)) for the road transport.

RE_a: Environmental costs (€/(t × trip)) for the stretches of the intermodal chain $\forall a \in \mathrm{A}$.

X_d: Relative probability of delivering/receiving a load for each node of the northern and southern regions (%) regarding other alternative nodes $\forall d \in$ DDMoS North: Iquique ($X_d = X_1 = 43\%$) and Antofagasta ($X_d = X_2 = 57\%$).

MoS South: Concepción ($X_d = X_3 = 75.95\%$) and Temuco ($X_d = X_4 = 24.04\%$).

X^c_{jz}: Relative probability of delivering/receiving a load for each node of the central region (%) regarding other alternative nodes for each MoS (MoS North and MoS South) and direction (north–south and south–north) $\forall z \in \mathrm{Z} \wedge \forall c \in \mathrm{ST} \wedge \forall j \in \mathrm{J}$.

TS_w: Time for every port operation during the maneuvering stage (h); $\forall w \in \mathrm{WW}$.

TVM: Time invested in intermodal transport (h).

TVU: Time invested in the unimodal alternative (road haulage) (h).

V_k: Average speed of the cranes for the spoke ports $\forall k \in \mathrm{K}$ (cycles/h).

V_m: Average speed of the cranes for the hub ports $\forall m \in \mathrm{M}$ (cycles/h).

VT: Speed of the truck (km/h).

Appendix B

See Table 12.

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