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Intermodal network design:

A three-mode bi-objective model applied to the case of Belgium

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Abstract Freight transport planning is nowadays encouraged to align with environmental objectives. Among those, climate change is of particular interest for many countries. In its White Paper on Transport, the European Commission considers intermodal transport as a potential solution for reducing environmental impacts. In order to make good strategic transport decisions, realistic decision support models for freight transport networks must

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be developed, so that insights can be derived for the different stakeholders of the transportation chain. This research proposes a bi-objective mathematical formulation which takes into account economic and environmental objectives, on a road and intermodal network with three modes of transport (road, intermodal rail, and intermodal inland waterways), and in which economies of scale of intermodal transport can be considered. With this model better fitting reality, an application to the Belgian case study provides practical information on how flows, terminal types and locations vary depending on the chosen policy, on the integration or not of economies of scale, on costs or emissions modifications and on the number of terminals to locate. Results show that the chosen policy influences the terminal type and the intermodal market share. The study also highlights the interest of intermodal transport on short distances, and the risk of flow exchanges inside the intermodal market share, rather than between road and intermodal transport.

Keywords Intermodal network design · Bi-objective · Nonlinear · Economies of scale · CO_2

1 Introduction

One of the most negative impacts of transport on climate change is the release of CO_2 emissions. Road transport represents around 20% of the total carbon dioxide emissions in Europe [17]. Nowadays, European authorities clearly encourage the transfer of freight flows from road to more environmentally friendly modes of transport such as inland waterway (IWW) or rail [15]. Intermodal transport is identified as an interesting solution for achieving the required transfer from road to less polluting modes of transport.

Intermodal transport is defined as the transportation of goods using two or more modes of transport, in the same loading unit, without handling of the goods themselves [47]. For ensuring intermodal competitiveness both in terms of economic and environmental issues, it is of strategic importance to correctly locate intermodal terminals [37]. The location of terminals determines the pre-and post-haulage distances of trucks between the terminals and the origin/destination nodes. If terminals are wrongly located, i.e. if the pre-and post-haulage distances are too long, the benefits obtained on the intermodal travel cannot compensate anymore for the higher costs and emissions of road transport.

Intermodal transport has been studied according to different perspectives ([5]; [35]) in the literature and an important part of research is concentrated on supporting the decision-making process ([32]; [7]; [8]; [46]).

In particular, network design problems have been addressed using several methodologies: agent-based models [43] , GIS-based models ([33]; [34]; [49]; [36]) or mathematical programming models ([3]; [2]; [40]; [24]; [45]; [44]; [30]; [6]; [42]; [48]).

Studies on intermodal network design mostly focus on a single objective. Most of the research concentrates on the minimization of the operational costs on the network ([2]; [40]; [24]; [45]; [21]). Some models focus on generalized costs of transport, including transport externalities ([49]; [42]; [48]). Single-objective optimization can also be applied to emissions minimization or modal split maximization [6]. Few articles of bi-objective modeling are available in intermodal transport applications. [44] use bi-objective optimization for balancing the network users' costs and the terminal operators' opening costs. In order to consider the environmental impact of trucks at maritime railroad terminals, [12] apply a bi-objective queuing model that minimizes both the number of shifted truck arrivals and the total waiting time of trucks in the queue.

With the exception of [21], who develop a path-based formulation allowing the use of several modes of transport, and [48], who focus on bi-level programming, the traditional location-allocation mathematical programming models in the literature are generally developed on a network which does not exceed two modes of transport ([3]; [2]; [40], [24]; [29]; [45]; [42]). Some papers however include road, rail and inland waterway transport ([33]; [34]; [36]), but in the framework of a GIS-based approach. The introduction of more than two modes of transport is important for better matching reality.

Intermodal transport provides the advantage of moving large quantities of goods and thus to possibly benefit from scale effects. Economies of scale can happen at several levels of the intermodal chain, i.e. during the long-haul transportation by a more environmentally friendly mode ([40]; [24]; [21]) or at the intermodal terminal, during the transshipment process ([29]; [49]; [48]). Economies of scale can be translated mathematically using different methods, e.g. nonlinear functions, discount factors, different values for different vehicle sizes or functions constituted by fixed and variables parts.

The objective of this research is to help closing the gap between freight transport network design and its impact on the environment, especially on climate change. This is done by proposing an innovative bi-objective intermodal location-allocation optimization model. The model evaluates the balance between economic (operational costs) and environmental (CO_2 emissions) objectives, in the framework of a network with three modes: road, intermodal rail, and intermodal IWW transport. The economies of scale of intermodal transport are incorporated using different vehicle sizes and piecewise linear approximations of nonlinear cost and emission functions. The integration of these characteristics contributes to the development of a more realistic formulation of transportation planning, in a political context where transportation strategies have to be aligned with environmental objectives. To highlight the practical usefulness of the model, it is applied to the Belgian case study. Thanks to its strategic perspective, the model gives insights to various actors of the freight transport network, in a societal context which focuses more and more on environmental issues. Policy-makers, intermodal terminal operators, road and intermodal transport companies and infrastructure managers can indeed gain insight on the strategies to follow, in terms of policy measure analysis, capacity, infrastructure design and transport flow planning. Indeed, the behaviour of road and intermodal flows may vary depending on the followed transportation strategy, in terms of the objective to pursue, or the number of terminals to locate. Sensitivity analysis is used to evaluate the evolution and robustness of the results, when the parameters related to costs, emissions, or to the number of terminals are modified.

The papers of [49], [36], [6], [42], and [48] are the most related to our research. [49] and [48] focus on bi-level optimization and consider CO_2 charges together with operational costs in the same objective function, while we present a bi-objective formulation which highlights the opposition between operational costs and CO_2 emissions in terms of intermodal network design. In addition, [49] and [48] integrate economies of scale at the intermodal terminal, whereas we look at economies of scale during the long-haul intermodal transport. [36] focus on the terminal operator's perspective using a GIS-based approach, while we formulate the mixed integer nonlinear model at a global level and provide decision-making tools to different stakeholders. We also explicitly take environmental issues into account, whereas [36] only consider them implicitly. [6] locate a single terminal. Alternatively, this work focuses on the location of several terminals between many origin and destination nodes. [6] focus on the Euclidian and Manhattan distances, and on approximated continuous demands, while we concentrate on the real distance and historical record of flow exchanges. We also offer the possibility to choose between road and two intermodal solutions, whereas [6] permit to select either road or intermodal transport. Our model is also subject to different constraints, not only related to demand satisfaction. [42] focus on road and rail transport, while we consider three modes and economies of scale of intermodal transport. We do not take into account subsidies and global external costs in a single objective function, but we solve a bi-objective model, in order to highlight the opposition between costs and CO_2 emissions minimization, in terms of terminal location and type.

The next section develops the problem formulation and the proposed mathematical model. Section 3 presents the experimental results of the application to the Belgian case. The last section highlights the main conclusions of the research work.

2 Problem formulation

The objective of the model is to propose a global vision of the impact of operational costs and CO_2 emissions on terminal location and type, and on the allocation of flows between road and intermodal transport. Even if a lot of stakeholders are involved in the decision process of intermodal network design, this paper assumes a single decision-maker at the strategic level ([2]; [29]; [42]), in order to provide decision-making support for different stakeholders of the system. Policy makers can gain insight by assessing the interest of locating new terminals inside their political zone of decision. They can also use the model to analyze the impact of policy measures such as the introduction of subsidies or the internalization of external costs. Intermodal terminal operators can benefit from improved information on the predicted volumes passing through their facilities and thus adapt the related services inside the terminal. Road and intermodal transport companies can be interested in identifying how the adoption of one or another policy could modify their market share. Information on flow distribution can also be used by rail, road and IWW infrastructure managers to determine the future transported volumes and thus plan the required capacities of the network.

The formulation allows determining the modal split between three modes: road, intermodal rail and intermodal IWW transport. Transport network design models often only focus on a specific intermodal transport mode ([2]; [40]; [24]) using the hub location theory ([1]; [20]), without considering the possible direct door-to-door road travel. Our modelling differs from the traditional hub system in the sense that non-hubs (i.e. non-terminal nodes) can be connected directly to each other using road transport, two intermodal terminals (hubs) are not necessarily connected, and finally the non-hub nodes can be connected to more than one terminal. The relaxation of these hypotheses better reflects reality [30].

The minimization of operational costs and CO_2 emissions mainly refers to energy optimization. Instinctively, we presume that the terminal locations do not differ too much from costs to emissions optimization. However, we also expect some diverging factors between both functions. For instance, repair and maintenance costs may be lower for road than for rail, whereas emissions are expected to be higher for road than for rail. This possible opposition between costs and emissions is taken into account by including both functions in a bi-objective optimization model.

For the environmental aspect, the focus is on climate change, using CO_2 emissions as its indicator. Only one type of externality is selected in order to identify its specific environmental impact on the terminal location problem. The choice for climate change is justified by the worldwide willingness to reduce the anthropic global warming effect. This is observed through big conventions and events such as the Kyoto Protocol or the regular United Nations Climate change conferences. Limiting the global warming effect is also part of the priorities of Europe [17], since heavy duty vehicles are responsible for 25% of road transport and 6% of total transport CO_2 emissions. CO_2 emissions are chosen as the environmental indicator because they represent the main greenhouse gas which influences climate change.

The model takes train and barge capacity into account. For rail transport, a single train size is considered. The number of trains to be used on each arc is optimized and the related load factor is then deduced. Rail cost and emission values are computed on the basis of this load factor. For IWW transport, the number and size of barges to be used on each arc are optimized and the related load factor is then deduced. Similarly to rail, IWW cost and emission values are computed on the basis of this load factor.

The formulation of the model which allows taking into account economies of scale of intermodal transport is developed hereunder.

The transportation units used for expressing costs are tonne.kilometers (t.km), barge.kilometers (barge.km) and tonnes (t).

2.1 Sets

T	set of types of barges, according to their size, indexed by $t \in \{1, \ldots, d\}$
V	set of trains, indexed by $v \in \{1, \ldots, f\}$
N	node set consisting of n demand nodes, indexed by $i, m \in \{1, \ldots, n\}$
H	existing and potential terminal (hub) set, ($H \subseteq N$) consisting of h nodes, indexed by $j, k \in \{1, \ldots, h\}$
N_0	set of potentially existing port nodes, rail and IWW terminals, inside the studied geographical area

N_1	set of demand nodes inside the studied geographical area, potential railroad terminals
N_2	set of demand nodes inside the studied geographical area, potential IWW-road terminals
N_3	set of railroad terminals located outside the studied geographical area
N_4	set of IWW-road terminals located outside the studied geographical area
N_5	set of demand nodes outside the studied geographical area
N	$= N_0 \cup N_1 \cup N_2 \cup N_3 \cup N_4 \cup N_5$
H	$= N_0 \cup N_1 \cup N_2 \cup N_3 \cup N_4$
H_R	$= N_0 \cup N_1 \cup N_3$
H_W	$= N_0 \cup N_2 \cup N_4$

2.2 Parameters

p	number of intermodal terminals to locate inside the studied geographical area
d_{im}	road distance between demand nodes i and m (in km)
s_{jk}	rail distance between terminals j and k (in km)
l_{jk}	IWW distance between terminals j and k (in km)
D_{im}	cargo demand from demand node i to demand node m (in t)
C^L_{im}	long-haul road transportation costs for travelling from node i to node m (in €/t.km)
C^P_{ij}	collection/distribution road transportation costs for travelling from node i to terminal j (in €/t.km)

C_{jk}^{R}	long-haul rail transportation costs for travelling from terminal j to terminal k (in €/t.km)
C_{jk}^{tW}	long-haul IWW transportation costs for travelling from terminal j to terminal k using a barge of size t (in €/barge.km)
E_{im}^{L}	long-haul road transportation emissions for travelling from node i to node m (in kg of CO_2/t.km)
E_{ij}^{P}	collection/distribution road transportation emissions for travelling from node i to terminal j (in kg of CO_2/t.km)
E_{jk}^{vR}	transportation emissions for travelling from terminal j to terminal k using the v^{th} train for the long-haul travel by rail (in kg of CO_2/t.km)
E_{jk}^{tW}	transportation emissions of a barge of size t for travelling from terminal j to terminal k for the long-haul travel by IWW (in kg of CO_2/barge.km)
C_j^T	handling operational costs at the terminal j (in €/t)
E_j^T	handling emissions at the terminal j (in kg of CO_2/t)
K_T	maximum capacity of a barge of size t (in t)
A	maximum capacity of a train (in t)

2.3 Decision variables

$$y_k = \begin{cases} 1 \text{ if a terminal is located at } k & \forall k \in N_1 \cup N_2 \\ 0 \text{ otherwise} \end{cases}$$

W_{im}	road flows from demand origin i to destination m (in t)	$\forall i, m \in N$

X^{i}_{jk}	flows from node i firstly routed through origin rail terminal j and then through destination rail terminal k (in t)	$\forall i \in N,\ \forall j,k \in H_R$
X^{vi}_{jk}	flows from node i firstly routed through origin rail terminal j and then through destination rail terminal k, using the v^{th} train for the long-haul travel by rail (in t)	$\forall v \in V,\ \forall i \in N,\ \forall j,k \in H_R$
Q^{i}_{km}	flows from origin i to destination m that are routed through rail destination terminal in k (in t)	$\forall i,m \in N,\ \forall k \in H_R$
F^{i}_{jk}	flows from node i firstly routed through origin IWW terminal j and then through destination IWW terminal k (in t)	$\forall i \in N,\ \forall j,k \in H_W$
V^{i}_{km}	flows from origin i to destination m that are routed through IWW destination terminal in k (in t)	$\forall i,m \in N,\ \forall k \in H_W$
M_t	number of barges of size t	$\forall t \in T$

2.4 Objective functions to minimize

$$\begin{aligned}
f_{costs} = & \\
& \sum_{i \in N} \sum_{m \in N} d_{im}\ C^L_{im}\ W_{im} \\
& + \sum_{i \in N_0} C^T_i\ W_{im} + \sum_{m \in N_0} C^T_m\ W_{im} \\
& + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} (d_{ij}\ C^P_{ij} + C^T_j)\ X^i_{jk} \\
& + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} s_{jk}\ C^R_{jk}\ X^i_{jk} \\
& + \sum_{i \in N} \sum_{k \in H_R} \sum_{m \in N} (d_{km}\ C^P_{km} + C^T_k)\ Q^i_{km} \\
& + \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} (d_{ij}\ C^P_{ij} + C^T_j)\ F^i_{jk} \\
& + \sum_{t \in T} \sum_{j \in H_W} \sum_{k \neq j \in H_W} l_{jk}\ C^{tW}_{jk}\ M_t \\
& + \sum_{i \in N} \sum_{k \in H_W} \sum_{m \in N} (d_{km}\ C^P_{km} + C^T_k)\ V^i_{km}
\end{aligned} \tag{1}$$

$$\begin{aligned}
f_{emissions} = & \\
& \sum_{i \in N} \sum_{m \in N} d_{im}\ E^L_{im}\ W_{im} \\
& + \sum_{i \in N_0} E^T_i\ W_{im} + \sum_{m \in N_0} E^T_m\ W_{im} \\
& + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} (d_{ij}\ E^P_{ij} + E^T_j)\ X^i_{jk} \\
& + \sum_{v \in V} \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} s_{jk}\ E^{vR}_{jk}\ X^{vi}_{jk} \\
& + \sum_{i \in N} \sum_{k \in H_R} \sum_{m \in N} (d_{km}\ E^P_{km} + E^T_k)\ Q^i_{km} \\
& + \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} (d_{ij}\ E^P_{ij} + E^T_j)\ F^i_{jk} \\
& + \sum_{t \in T} \sum_{j \in H_W} \sum_{k \neq j \in H_W} l_{jk}\ E^{tW}_{jk}\ M_t \\
& + \sum_{i \in N} \sum_{k \in H_W} \sum_{m \in N} (d_{km}\ E^P_{km} + E^T_k)\ V^i_{km}
\end{aligned} \tag{2}$$

2.5 Subject to

$$\sum_{k \in N_1 \cup N_2} y_k \leq p \tag{3}$$

$$y_k = 1 \qquad \forall k \in N_0 \cup N_3 \cup N_4 \tag{4}$$

$$D_{im} = W_{im} + \sum_{k \in H_R} Q^i_{km} + \sum_{k \in H_W} V^i_{km} \qquad \forall i, m \in N \tag{5}$$

$$\sum_{m \in N} D_{im} = \sum_{m \in N} W_{im} + \sum_{j,k \in H_R} X^i_{jk} + \sum_{j,k \in H_W} F^i_{jk} \qquad \forall i \in N \tag{6}$$

$$\sum_{k \in H_R} X^i_{jk} \leq y_j \sum_{m \in N} D_{im} \qquad \forall i \in N, \forall j \in H_R \tag{7}$$

$$\sum_{j \in H_R} X^i_{jk} \leq y_k \sum_{m \in N} D_{im} \qquad \forall i \in N, \forall k \in H_R \tag{8}$$

$$\sum_{k \in H_W} F^i_{jk} \leq y_j \sum_{m \in N} D_{im} \qquad \forall i \in N, \forall j \in H_W \tag{9}$$

$$\sum_{j \in H_W} F^i_{jk} \leq y_k \sum_{m \in N} D_{im} \qquad \forall i \in N, \forall k \in H_W \tag{10}$$

$$\sum_{j \in H_R} X^i_{jk} = \sum_{m \in N} Q^i_{km} \qquad \forall i \in N, \forall k \in H_R \tag{11}$$

$$\sum_{j \in H_W} F^i_{jk} = \sum_{m \in N} V^i_{km} \qquad \forall i \in N, \forall k \in H_W \tag{12}$$

$$\sum_{t \in T} M_t \; K_t \geq \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} F^i_{jk} \tag{13}$$

$$X^i_{jk} = \sum_{v \in V} X^{vi}_{jk} \qquad \forall i \in N, \forall j, k \in H_R \tag{14}$$

$$X^{vi}_{jk} \leq A \qquad \forall v \in V, \forall i \in N, \forall j, k \in H_R \tag{15}$$

$$W_{im} \geq 0 \qquad \forall i, m \in N \tag{16}$$

$$X^{vi}_{jk} \geq 0 \qquad \forall v \in V, \forall i \in N, \forall j, k \in H_R \tag{17}$$

$$Q^i_{km} \geq 0 \qquad \forall i, m \in N, \forall k \in H_R \tag{18}$$

$$F^i_{jk} \geq 0 \qquad \forall i \in N, \forall j,k \in H_W \qquad (19)$$

$$V^i_{km} \geq 0 \qquad \forall i,m \in N, \forall k \in H_W \qquad (20)$$

$$y_k \in \{0,1\} \qquad \forall k \in H \qquad (21)$$

Equations 1 and 2 respectively stand for the total operational costs and emissions of transport companies. These equations are divided into: (i) door-to-door road costs/emissions, (ii) transshipment costs/emissions between sea and road, (iii) railroad intermodal costs/emissions and (iv) IWW-road intermodal costs/emissions. Elements (iii) and (iv) are again subdivided into (a) pre-haulage costs/emissions by road, (b) transshipment costs/emissions at origin intermodal terminal, (c) long-haul travel costs/emissions by rail or IWW, (d) transshipment costs/emissions at the destination terminal and (e) post-haulage costs/emissions by road.

Constraint 3 suggests that a maximum of p terminals can be located. This constraint reflects that building intermodal terminals is not free of charge so that only a certain number of terminals can be constructed, with respect to the available budget. Constraints 4 ensure that the already existing terminals are open. Constraints sets 5 and 6 respectively guarantee that the demand between each origin i and destination m pair is satisfied either by road, railroad or IWW-road transport and that all the flows are leaving their origin by one of the three modes. Constraints 7 to 10 state that no flow can pass through an intermodal terminal if this terminal is not open. Constraints 11 and 12 ensure flow conservation for rail and IWW transport. Constraint 13 ensures that the number of available barges of all types is sufficient for satisfying the demand transported by IWW. Constraints 14 guarantee flow conservation between road transport by truck and rail transport by train. Constraints 15 ensure that the capacity of the train is not exceeded. Finally constraints 16 to 20 are non-negativity constraints for flows, while constraints 21 define variables y_k as binary variables.

The proposed model is bi-objective and can account for economies of scale of intermodal transport. The bi-objective formulation is solved using the exact ε-constraint resolution technique of [11]. The method consists in transforming a multi-objective problem into single-objective optimization, by only keeping one objective function to optimize. Other objective functions are introduced as constraints of the model, lower or equal to a value ε [41]. In this study, the CO_2 emission function is introduced as a constraint of the cost minimization problem. Economies of scale of intermodal transport are modeled using nonlinear functions of the weight. The latter are approximated by a piecewise linear function, so as to permit the use of linear programming solvers for the problem resolution. Detailed explanations on the solution methodology can be found in online Appendix A.

The following sections develop the results of the linear and nonlinear approaches. A sensitivity analysis of the parameters related to costs, emissions, and number of terminals is then performed to check the robustness of the model.

3 Experimental results

The model is tested on the Belgian network for several reasons. First, the country has a high density of road, rail and IWW infrastructure. Then, new intermodal terminals are still currently being added to the network, e.g. with the development of the new Trilogiport intermodal platform in Liege. Thanks to its strategic location at the heart of Europe, important quantities of freight flows are also transiting through the country. Moreover, Belgium has one of the worst European performances in terms of air quality [16], which makes this case interesting in terms of environmental analysis. The use of intermodal transport is often recommended on medium and long distances. This case allows analyzing the performance of road and intermodal transport on short distances. Belgium has already been used as a case study by several authors to identify the impact of policy measures on the modal shift ([33]; [34]; [42]), and to evaluate if opening additional intermodal terminals is still desirable from the terminal operator's perspective [36].

Demand containerized data consists in road, rail and IWW flows and originates from [9]. The original 2005 database has been extrapolated to 2010. The second-level Nomenclature of Territorial Units for Statistics (NUTS 2) flows are disaggregated to a NUTS 3 level, using the number of companies of productive sectors in those regions as the proxy indicator. The demand for each region is concentrated on a single generation node, called centroid and chosen for the importance of the cities in the NUTS 3 region and the existence of a rail/IWW platform nearby. The model considers flow exchanges inside Belgium and between Belgium and some of its neighboring regions in the Netherlands, Germany, France, and Luxembourg. The already existing terminals for rail and IWW outside Belgium, as well as the already existing sea terminals in Belgium (Antwerp, Zeebrugge and Ghent) are taken into account. Supply data consists in the road, rail [9] and IWW [38] networks of transport, and their associated costs.

In the reference case, the maximum number of IWW and rail terminals to be located is fixed to 15. It corresponds to the sum of the most important rail, IWW and three-mode terminals currently available in Belgium. Sea terminals of Antwerp, Ghent and Zeebruge are not considered for determining the total number of terminals to open, as they are already assumed to be open, both for IWW and rail. The limit between short-haul and long-haul travel is fixed to 300 km, which is the accepted distance by the European Commission [15].

3.1 Linear approach

This section aims at presenting the results of the bi-objective linear model.

The definition of the linear cost and emission functions can be found in online Appendix B. Fig. 1 shows the Pareto front for the bi-objective model under the linear approach in terms of relative values. The relative optimal costs-emissions pairs for 11 solutions varying from the minimum cost scenario (reference value) to the minimum emission scenario are presented.

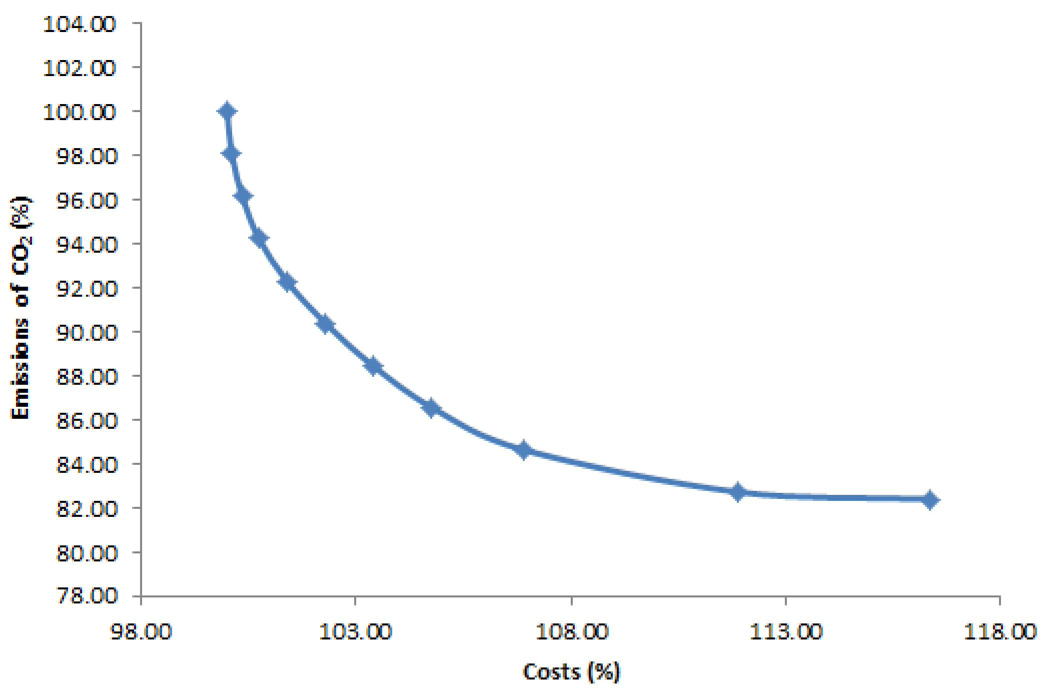

Fig. 1 Pareto front for the bi-objective model in the linear case

The Pareto front shows that emphasizing more environmentally friendly transport implies additional financial means. Table 1 provides the relative optimal objective values, the flow distribution values and the number of located terminals, under the two extreme points of the Pareto curve.

Table 1 Results of the optimal costs and emissions minimization cases

Reference scenario	Relative objective (cost or emission) value	Absolute road flow values	Absolute rail flow values	Absolute IWW flow values	Number of located rail terminals	Number of located IWW terminals
Costs min	100%	76%	15%	9%	10	5
Emissions min	100%	26%	24%	50%	6	9

Fig. 2 illustrates the flow distribution of the extreme cases of the Pareto curve, i.e. the situation, with the minimum possible costs and the minimum possible emissions.

In the cost minimization case, compared to the real modal split of the studied region, IWW flows are underestimated in favor of road flows. For 2011, the flow distribution in Belgium and in its neighboring countries (mainly the Netherlands, Germany and France), is on average 68% for road, 15% for rail and 18% for IWW transport [19]. The difference between statistics data and the modal split of the model is explained by the fact that our origin-destination matrix only takes into account containerized flows, whereas IWW is generally used for bulk transportation [10]. The actual modal split is also influenced by the awarded subsidies [42], which are not included in the current particular analysis. Furthermore, since the objective of the model is to minimize costs, only the cheapest mode of transport is used for transporting goods for a specific

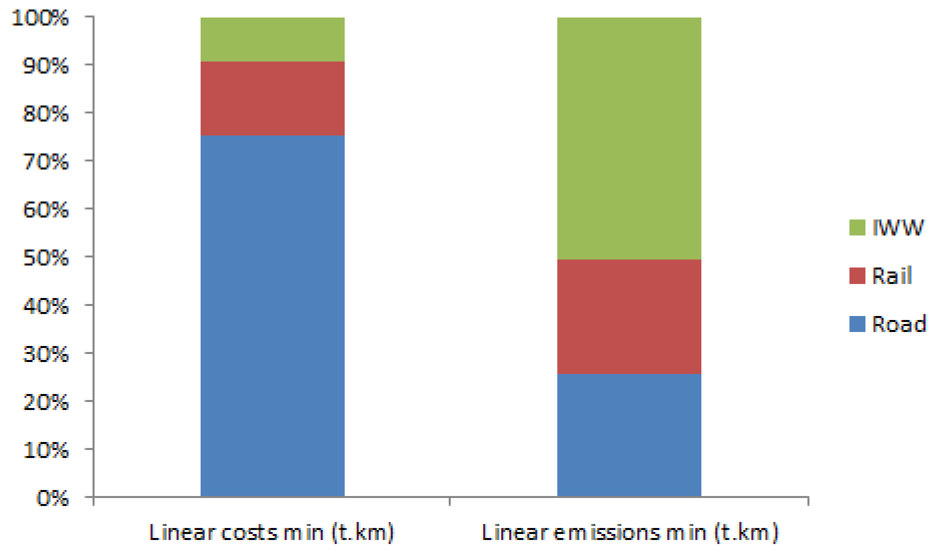

Fig. 2 Flow distribution (t.km) for costs and emissions minimization in the linear case

origin-destination pair. For origin-destination pairs with volumes, the modal choice greatly influences the general market share distribution in t.km.

The predominance of rail transport under costs minimization is explained by the low value of the used rail cost function compared to IWW. In addition, there are not as many IWW as rail potential locations for terminals, which leads to increased distances using barges compared to trains. Under emissions minimization, the switch to more IWW transport is also explained by the values of the emission functions. Even if the distance by barge is longer than the distance by train, the small unit IWW emissions can compensate for the larger distances.

When costs are minimized, 5 IWW and 10 rail terminals are located. When emissions are minimized, 6 IWW and 9 rail terminals are open. Even if the type of terminal may change from costs to emissions minimization, more than half of the terminals are located exactly at the same place. This means that the policies aiming at optimizing costs and emissions are not totally in opposition, in terms of terminal location.

The model locates 15 terminals in 44 possible NUTS 3 regions. Most of the locations found by the model correspond to the real implementations of the main intermodal terminals in Belgium. However, some minor changes can also be noticed. These differences can be explained by the model's focus only on costs and emissions efficiency. However, other parameters also influence the location of terminals, such as political issues, land availability and equipment. The current model assumes as a potential terminal location any centroid of a region that can physically be accessed by train and IWW, which does not necessarily correspond to an already existing terminal.

The application of the linear model to the Belgian case study shows that the cost effort for achieving a same amount of reduction of CO_2 emissions becomes larger as one approaches the emissions optimality scenario. The chosen policy (costs or emissions minimization) leads to the location of different types of intermodal terminals (rail or IWW) and also influences the intermodal market share. Regardless of the pursued objective, intermodal transport is always used, even on small networks with reduced distances like Belgium. Finally, most of the locations found by the model correspond to the 15 main existing terminals in Belgium, or are located in the same region, which highlights the realism of the proposed modeling approach.

3.2 Nonlinear approach

This section identifies how the integration of economies of scale of intermodal transport impacts the results of the linear approach. The definition of the cost and emission functions are described in online Appendix C. The focus is on the two extreme cases of the Pareto curve, i.e. costs minimization and emissions minimization. The terminal configurations obtained under the linear approach are tested using the nonlinear parameters, in order to compare the flows obtained in the linear and nonlinear cases.

Fig. 3 details the flow distribution between the different modes of transport under the nonlinear parameters.

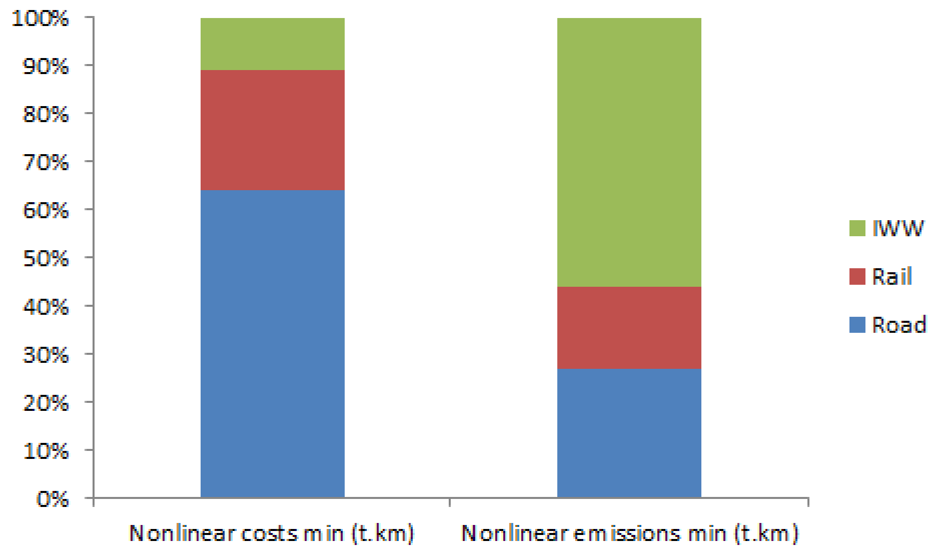

Fig. 3 Flow distribution (t.km) for costs and emissions minimization in the nonlinear case

In the nonlinear case, going from costs to emissions minimization also leads to an increase of the use of intermodal transport. Inside intermodal transport, rail transport is preferred for achieving cost efficiency, but IWW is favored when it comes to optimize the environmental perspective. The chosen policy therefore influences the actual modal split.

Between the linear and nonlinear approach, a market share increase of 10% for rail and 2% for IWW is observed under the costs minimization case. When economies of scale are integrated, 12% of the road flows are thus transferred to the intermodal market share. For the emissions minimization case, a market share decrease of 7% for rail and an increase of 6% for IWW are identified when taking into account economies of scale, i.e. a transfer of 1% from road to intermodal market share. In the minimum emissions case, the main flow transfer between the linear and nonlinear approach is observed inside the intermodal market share, rather than between road and intermodal transport.

Taking into account economies of scale in the model encourages a more intensive consolidation of flows, leading to reduced global costs and emissions for intermodal transport, with a higher use rate of this mode. This explains the increased intermodal market share, when going from the linear to the nonlinear approach.

The number and size of barges used under the nonlinear approach differs from costs to emissions minimization. Indeed, around three times more barges are used when emissions are minimized than when costs are minimized. This is coherent with the observed increase of IWW market share from costs to emissions minimization. Moreover, the split between the different types of barges is also different. Under costs minimization, 3% of the barges are small, 71% are medium and 26% are large. Under emissions minimization, small barges represent 47% of the IWW flows, medium barges correspond to 37% and large barges have 16% of the IWW market.

Under the emission minimization policy, more IWW terminals are open, all of which not necessary accessible through medium barges (geographical constraints), which may explain the larger part of used small barges. These results are interesting for infrastructure managers and barge operators, since they show that the chosen policy (economic or environmental) influences the way in which networks and vehicles should be planned in the future.

For both objective functions, in the linear and nonlinear cases, the model advices the use of intermodal transport. This result shows that, to the contrary of what is recommended by the European Commission in its White Paper [15], intermodal transport is also viable and could therefore also be used on short distances. Indeed, most of the distances of the case study on Belgium are below 300 km. This insight has already been highlighted by [6], who state that high volumes and short pre- and post-haulage distances make intermodal transport attractive on short and medium distances. The importance of short pre- and post-haulage distances in terms of intermodal competitiveness, especially from the perspective of externalities, has also been underlined in [37]. The conclusions of [26], showing that, in some cases, the internalization of external costs may lead to a lower attractiveness of intermodal transport, rather than when only operational costs are considered, reinforces the need for particularly considering short pre- and post-haulage distances. As [49] and [48], our results also show the strong link between the terminal network configuration and the amount of CO_2 emissions.

To summarize, in the limited case of Belgium and its neighborhood, the nonlinear and linear approaches both encourage more intermodal transport in order to reduce the environmental impact of transport. Furthermore, introducing economies of scale of intermodal transport in the modeling modifies the modal split, favoring intermodal transport both for costs and emissions minimization.

3.3 Computational performance

The optimization steps were performed on a personal computer (Windows 10 Pro, Intel Xeon 2.1 GHz, 32 GB of RAM) with CPLEX 12.63.

The problem developed in this paper is complex to solve. The model uses an origin destination matrix constituted by 88 origin and 88 destination nodes. The number of flow variables is 88^2 for road, $2 * 88^3$ for intermodal rail, and $2 * 88^3$ for intermodal IWW transport. As [13], the model uses variables of maximum size $O(n^3)$. The problem size, in terms of the number of variables, is thus reduced by a factor n, compared to most of the hub location models [20], where flows are expressed using variables with four indices.

For the example under study, the linear single cost minimization problem is easier to solve than the linear single emission minimization problem. The single cost minimization location-allocation model is solved in 69 seconds. The single emission minimization location-allocation problem is solved in about 80 times the time required for the single cost case. The difference in computational times may be explained by the unit emission values, which allow for more use of the three modes of transport in the emission rather than in the cost minimization case, in which road transport is clearly favored. Whatever the optimized objective, we therefore expect shorter computational times, as long as the differences between the unit modal parameters increase.

Solving the cost minimization problem, and then determining the corresponding optimal emission value (i.e., defining the Pareto optimal solution) results in a computational time of 983 seconds. It is 14 times the time required for finding a solution which is optimal in terms of cost.

Having generated the starting point of the Pareto curve, the inclusion of the additional epsilon-constraint leads to run times varying between 2 and 14 times the time required for the optimization without the additional constraint on the emissions. Each point of the Pareto curve is generated in times between 1,912 and 14,069 seconds. The average time for solving one point of the Pareto curve is 7,339 seconds. The standard deviation of the solving times is 4.06.

When dealing with economies of scale, a single allocation problem is solved and the resolution times are less than 450 seconds.

Since our model solves a problem at the strategic level of transport planning, the resolution times do not limit its usefulness for decision-makers. At the NUTS 3 level, the model allows solving location-allocation problems for a small geographical region like Belgium. In order to obtain similar computational performances for bigger geographical areas, the level of aggregation of flows should be increased. If larger instances with the same degree of disaggregation are analyzed, further solution methods (e.g. [45]) will be needed.

3.4 Sensitivity analysis

The goal of this section is to test the robustness of the model, by identifying whether the results change substantially, when the input parameters are modified. Sensitivity analysis is performed on the parameters related to costs, emissions and the number of terminals.

3.4.1 Costs

Table 2 compares the results of the linear cost minimization case analyzed here above (Table 1), with scenarios of 10% increase and decrease of the initial parameter values.

The cost and flow variations are the respective relative and absolute differences in total costs and flows, compared to the cost minimization scenario. For instance, an increase of 10% of the transshipment cost leads to total costs relatively 1.16% higher than the ones obtained in the cost minimization scenario. Regarding flows, an increase of 10% of the transshipment cost leads to an absolute increase of 2.89% of the road market share, compared to the cost minimization scenario. The relative variation of the total costs is smaller than the relative variation of the cost parameters. Road external cost is the parameter that mostly influences the modification of total costs (respectively +8.01% and -8.23% when road costs are increased and decreased). This is expected since road activities have the greater modal share in the initial scenario and they influence the model in direct road transfers, but also during

Table 2 Sensitivity analysis of the cost parameters

Cost min scenario	Relative cost variation	Absolute road flow variation	Absolute rail flow variation	Absolute IWW flow variation	Rail terminals	IWW terminals	Identical locations
Transshipment cost: +10%	+1.16%	+2.89%	−1.36%	−1.53%	10	5	15/15
Transshipment cost: −10%	−1.23%	−0.91%	+0.75%	+0.16%	10	5	14/15
IWW cost: +10%	+0.17%	+1.16%	+1.49%	−2.65%	11	4	14/15
IWW cost: −10%	−0.34%	−1.39%	−6.24%	+7.63%	9	6	14/15
Road cost: +10%	+8.01%	−3.05%	+3.22%	−0.17%	11	4	14/15
Road cost: −10%	−8.23%	+5.05%	−1.98%	−3.07%	11	4	13/15
Rail cost: +10%	+0.36%	+0.03%	−7.15%	+7.12%	9	6	14/15
Rail cost: −10%	−0.56%	−0.38%	+3.02%	−2.64%	11	4	14/15

the pre- and post-haulage stages of intermodal transport. When road costs are modified, most of the flow distribution changes are observed between road and intermodal market shares. However, when the costs of intermodal long-haul modes are varied, a transfer of flows inside the intermodal market share is observed. This result highlights the risk of switch of modes inside the intermodal market share, rather than between intermodal and all-road transport [33]. As expected, the general flow distribution is affected by changes in cost factors. However, the absolute variation never exceeds 8%. The terminal locations mainly remain the same, in each of the studied scenarios. However, some slight switch in terminal type is noticed, depending on the cost variation under study. At most two terminals are different from the initial solution.

When a different terminal is located, only two different locations are chosen, whatever the scenario. The terminal location, type and flow distribution thus seem robust to cost variations.

3.4.2 Emissions

Table 3 compares the results of the linear emission minimization case analyzed here above (Table 1), with scenarios of 10% increase and decrease of the initial parameter values.

Table 3 Sensitivity analysis of the emission parameters

Emission min scenario	Relative emission variation	Absolute road flow variation	Absolute rail flow variation	Absolute IWW flow variation	Identical rail terminals	Identical IWW terminals
Transshipment emission: +10%	+0.58%	+1.66%	−0.34%	−1.32%	5/6	9/9
Transshipment emission: −10%	−0.61%	−1.69%	+1.98%	−0.29%	6/6	9/9
IWW emission: +10%	+1.06%	+1.97%	+0.30%	−2.27%	5/6	9/9
IWW emission: −10%	−1.12%	−0.43%	−1.17%	+1.60%	6/6	9/9
Road emission: +10%	+6.96%	−3.10%	+3.24%	−0.14%	6/6	9/9
Road emission: −10%	−7.23%	+3.54%	−2.61%	−0.93%	5/6	9/9
Rail emission: +10%	+1.11%	+2.64%	−3.27%	+0.63%	5/6	9/9
Rail emission: −10%	−1.38%	−2.30%	+12.97%	−10.67%	6/6	6/9

The relative variation of the total emissions is smaller than the relative variation of the emission parameters. The greatest gap is also observed for the scenarios where road emissions are modified. Global emissions are thus more sensitive to road than to other modes of transport. The flow distribution varies according to the scenario but the changes are limited in most of the cases. Larger market share variations are only observed in the scenario where rail emissions are decreased. Flow transfers mainly occur inside the intermodal market share, between rail and IWW transport. These results highlight again the risk of flow transfers inside the intermodal market share, rather than between road and a more environmentally friendly mode. Most of the terminal locations and types remain the same, whatever the scenario. The identical structure of terminal locations and types is observed in three out of eight scenarios. In four other cases, only one rail terminal is placed at another location (identical for each of these four scenarios). When rail emissions are reduced, three IWW terminals are replaced by rail terminals, which is coherent with the observed market share variation. The terminal location, type and flow distribution thus seem robust to emission variations.

3.4.3 Number of terminals

In order to test the parameter p, and its effect on the model, we varied its value from 10 to 16 terminals, both on the linear and nonlinear approaches. We also tested two extreme cases, i.e. a very small (2) and a very high (24) number of located terminals. Results show that the model is robust in terms of terminal locations. Indeed, when allowing $p + 1$ terminals to be opened, the model locates exactly the same terminals as in the p-configuration, and opens an additional terminal. The locations and types of terminals are thus consistent, whatever the value of p.

Under the linear cost optimization, the road market share progressively decreases with the increasing number of terminals. This behaviour is understandable since locating more terminals reduces the pre- and post-haulage costs of intermodal transport, and thus increases its competitiveness. A maximum of 8% of the road flows are transferred to the intermodal market share, between the location of 2 and 24 terminals. This means that, on several connections, even by increasing the number of terminals, i.e. by decreasing the pre- and post-haulage distances, the long-haul costs of rail and IWW are not low enough to compensate for the transshipment and pre- and post-haulage costs of intermodal transport. This modal transfer of 8% from road to more environmentally-friendly modes is far from the targeted flow transfers of 30% or 50% expressed in the European White Paper on Transport [15]. The main absolute transfers of flows happen between road and rail transport. Intermodal IWW and rail transport are similar in terms of cost structure. Flows are thus transferred from road to rail and not IWW, because rail long-haul costs are more attractive. In addition, rail terminals can be implemented at much more locations than IWW terminals (due to geographical constraints), which enhances their accessibility.

For the nonlinear cost optimization, a decrease of the road market share to the benefit of intermodal transport is observed until $p = 13$, i.e. less than the number of currently existing main terminals in Belgium. For every further additional terminal, the ratio between the intermodal and road market share remains the same. In the nonlinear case, there is thus some limitation in the flow exchange between road and intermodal transport. At some point, flows are simply transferred from one to another terminal, highlighting the self-cannibalization issue of intermodal transport. Results show that this phenomenon can happen either between the same type of terminals or between rail and IWW terminals. The absolute difference of road market share between the smallest and the highest amount of located terminals is bigger for emission (22%) than for cost optimization (8%). The modal split between road and intermodal transport is thus more sensitive to the number of terminals, when emissions are optimized, rather than when costs are optimized.

In the linear emission optimization, the flow exchanges happen between the three modes of transport. Flows are first mainly transferred from road to IWW, but when reaching a number of 15 terminals, only additional rail terminals are open. Some IWW flows are thus replaced by rail flows, which increases the rail market share to the detriment of IWW. Again, this underlines the risk of flow exchange inside intermodal transport rather than between road and intermodal transport.

For the nonlinear emission minimization, the intermodal market share also increases with the increasing number of terminals. An increase of the IWW market share is observed until $p = 14$, where this market share starts to decrease. This is explained by reduced flows passing through certain terminals, which leads to barges less charged and thus to reduced economies of scale.

4 Conclusions

This research develops and solves a new bi-objective location-allocation optimization model for intermodal transport under economies of scale. The model includes three modes: road, intermodal rail and intermodal IWW transport. It focuses on a bi-objective formulation, for identifying the trade-off between economic and environmental goals. The latter are estimated through CO_2 emissions, main greenhouse gas responsible for climate change. The economies of scale of intermodal transport can also be taken into account, using different sizes of vehicles for IWW and nonlinear cost and emission functions for rail.

The characteristics of the model allow a better matching with reality, and provide interesting insights to the stakeholders of the freight transportation chain. Indeed, the obtained results in terms of modal split and intermodal terminal location and type can be used by public authorities, infrastructure and terminal managers, or road, rail and IWW carriers to plan their strategic future decisions in alignment with environmental perspectives.

A case study on Belgium reveals interesting information regarding the impact on flow distribution, terminal type, and terminal location, of the followed economic or environmental policy, of the consideration or not of economies of scale, of the structure of costs and emissions, and of the number of located terminals.

The case study shows that different terminal types and modal splits are obtained, depending on the economic- or environmental-oriented policy that is considered. Similarly, the chosen policy affects the modal split inside the intermodal market share. Locations may change according to the economic or environmental desired outcome, but generally most of the terminals remain the same.

No matter if economies of scale are integrated or not, an increase of the intermodal market share is observed going from cost to emission minimization. An increased use of intermodal transport is thus suggested for achieving the environmental objectives related to climate change. Results of the linear and nonlinear cases underline the viability and interest of using intermodal transport on short distances. When economies of scale are integrated, more road flows are transferred to the intermodal market share, compared to the linear case.

Slight modifications of the unit costs and emissions of the different modes of transport do not provide significant impacts on the terminal location and flow distribution. This shows the robustness of the model but also highlights the issue that modifying slightly the performance of one mode in terms of costs or emissions (for instance through improved technologies) does not necessary lead to an important modification of the modal split. Moreover, results of the sensitivity analysis also illustrate that modifying road costs or emissions leads to flow transfers between road and intermodal transport, whereas modifications of rail or IWW costs or emissions generate flow exchanges between rail and IWW, inside the intermodal market share.

The terminal locations remain stable when the maximum number of allowed terminals is modified. The modal split behaviour is however different, when economies of scale are taken into account or not. Indeed, with linear costs and emissions, increasing the number of terminals continuously increases the intermodal market share, due to reduced pre- and post-haulage distances. When economies of scale are modelled, the decrease of the road market share is observed only until a certain number of terminals. After this threshold, flows are transferred from one to another terminal, highlighting the risk of self-cannibalization of terminals. Indeed, more terminals means less flows through them, lower possibilities of consolidation, and thus lower economies of scale.

The tests on the Belgian case study reveal that intermodal transport should be more used when environmental goals are followed. These outcomes confirm and support the usefulness of the European policies which encourage the transfer of road freight to more environmentally friendly modes such as rail or IWW. However, the results also underline the risk of flow transfers inside the intermodal market share, rather than between road and intermodal transport.

This research can be extended in future studies, by using other types of externalities to represent the environmental impact. Other applications of the model can also be developed, such as the analysis of new policy scenarios and the assessment of the impact of improvement in environmental friendliness of specific modes. The model can also be applied to another geographical area, where intermodal network design is still in progress. The strategic evaluation in terms of economic and environmental perspective of a new terminal location makes thus full sense in these areas in need of intermodal network design expertise.

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A Solution methodology

This section aims at presenting the methodological issues used in the solution of the bi-objective model with economies of scale of intermodal transport. The resolution method of the bi-objective model is first presented. The way in which nonlinear economies of scale are dealt with is then explained.

A.1 Bi-objective optimization

The proposed bi-objective terminal location-allocation model is a particular multi-objective problem. Its resolution generates Pareto optimal (or non-dominated) solutions, i.e. solutions for which none objective function value can be improved without worsening the value of another one. We solve the bi-objective problem by using the exact ε-constraint resolution technique of [11]. The method consists in transforming a multi-objective problem into single-objective optimization by only keeping one objective function to optimize, and introducing the other objective function as a constraint of the model, lower or equal to a value ε [41]. In this study, we introduce the CO_2 emission function as a constraint of the costs minimization problem. Instead of classically generating the ε values by determining a range of values in which it should vary, we generate the next ε value, directly based on the previous obtained optimal solution.

Algorithm 1 represents the methodology used for obtaining the Pareto-optimal solutions of the bi-objective model thanks to the exact ε-constraint method. Here are some details about its content:

– $MC(E)$ (respectively $MC'(E)$) is the model:

  Min f_{costs} s.t.

  (3)-(21)

  $f_{emissions} < E$ (respectively $f_{emissions} \leq E$)

– $ME(C)$ is the model:

  Min $f_{emissions}$ s.t.

  (3)-(21)

  $f_{costs} \leq C$

– i is the index of the step of the algorithm.

Algorithm 1 Generation of Pareto optimal solutions

```
SolveME(∞)
if ME(∞) has a solution then
    minE ← Value[f_emissions]
    SolveMC'(minE)
    C' ← Value[f_costs]
    i = 0
    E[0] = ∞
    while E ≥ minE do
        Solve MC(E[i])
        if MC(E[i]) has a solution then
            C[i] ← Value[f_costs]
            Solve ME(C[i])
            E[i] ← Value[f_emissions]
            P[i] = (C[i], E[i])
            i ← i + 1
            E[i] ← Value[f_emissions] − s
        end if
    end while
    P[i] = (C', minE)
else
    Stop
end if
```

A minimization of emissions is performed, with costs set to infinite. The resulting emission value is assigned to the variable $minE$. The minimum cost related to this minimum amount of emissions $minE$ is then computed and assigned to the variable C'. We thus have one of the two extreme points of the Pareto curve $(C', minE)$, which corresponds to the minimum possible emissions. The algorithm then initializes the value of the emissions to infinite. The loop starts with the generation of the other extreme point of the Pareto curve, with the minimum possible costs. For this purpose, costs are minimized and no constraints are applied on the emissions. Even if this solution is optimal in terms of costs, it is not necessarily optimal for the minimization of emissions. To ensure Pareto optimality, the model where emissions are minimized subject to the fact that costs are equal to or lower than the obtained cost value is thus solved. The other extreme point of the Pareto curve $(C[0], E[0])$ is thus generated. $E[0]$ is the first value of epsilon that is identified. Based on the optimal solution at the previous iteration, another Pareto optimal solution is generated by solving the model where the costs are minimized, subject to the fact that the emission values should be strictly lower than the ones obtained at the preceding iteration of the optimization $(E[0])$. Solving this model gives a cost value $C[1]$. To ensure the Pareto optimality, the same model is again solved by minimizing emissions, subject to the fact that the costs are less or equal to $C[1]$. A second Pareto optimal solution $(C[1], E[1])$ is then generated. $E[1]$ is the second identified epsilon value. The value of $C[1]$ is higher than the one of $C[0]$ but the value of $E[1]$ is smaller than the one of $E[0]$. One thus goes down along the Pareto front.

The loop goes on until the minimum value of emissions by the step size (s) is reached. This step size is used in order to avoid generating infinity of Pareto optimal solutions.

A.2 Piecewise linear functions

Economies of scale of transport are generally represented using a classical discount factor for the axes with high quantities of flows. The problem of this modeling is that this discount factor is often fixed, whatever the quantity transported, and does not really reflect the benefits generated for different levels of utilization [28]. There is therefore a need to integrate economies of scale in a different way. To account for economies of scale of rail transport, we use nonlinear functions of the weight transported. The concave increasing cost terms are approximated by a piecewise linear function, so as to permit the use of linear programming solvers for its resolution.

Identifying the piecewise linear function consists in determining the different segments that define the function, by isolating several breakpoints. The piecewise linearization is done in the simplest way [4], by cutting the function in segments of equal size. This is performed by choosing a set of breakpoints, uniformly distributed in the interval, between the minimum and maximum flows that are transported yearly.

Once the piecewise linear function has been identified, it should be practically modeled. The multiple choice model [27] is used for this purpose.

$$\sum_{k=1}^{d} w_k = x \tag{22}$$

$$\sum_{k=1}^{d} z_k = 1 \tag{23}$$

$$b^{k-1}\ z^k \leq w_k \leq b^k\ z^k, \qquad \forall k = 1,\dots,d \tag{24}$$

$$\sum_{k=1}^{d} (m_k\ w_k + a_k\ z_k) = y \tag{25}$$

$$z_k \in \{0,1\} \qquad \forall k = 1,\dots,d \tag{26}$$

The modeling is based on the introduction of two additional sets of variables. The value of w^k is equal to x, if x lies in the k^{th} out of d intervals and 0 otherwise. The value of z_k is equal to 1 if x lies in the k^{th} interval and 0 otherwise. The combination of constraints 22 and 24 ensures that only one w^k is equal to x, and that this happens only if x is in the k^{th} interval. The combination of equations 23 and 26 makes sure that only one z_k is equal to 1 and that this happens when x is in the k^{th} interval. Finally, constraint 25 determines the value of y as the linear combination of m_k and a_k, where m_k is the slope of the k^{th} segment and a_k is the interception of this segment with the y-axis, when it is extended until reaching the y-axis.

B Cost and emission functions of the linear approach

Unit costs functions for road are based on [25] and [26]. Unit road operational costs for long-haul travels (C^L_{im}) are computed as $0.2676 d_{im}^{-0.278}$/t.km, where d_{im} stands for the road distance between origin i and destination j and an average load factor of 0.85 [14] is assumed. Unit road operational costs for collection/distribution travels (C^P_{ij}) are equal to $0.3791 d_{jk}^{-0,278}$/t.km, with a considered load factor of 0.6 [14]. Unit road costs are nonlinear with the distance traveled.

Unit IWW costs (C^{tW}_{jk}) for a barge of size t are based on a study of [39]. In this approach, a single type of barge is considered. The capacity of this boat is determined as the maximum capacity of the European Conference of the Ministers of Transport (ECMT) class Va of barges, i.e. 3,000 t. The IWW costs for this average size barge are estimated to 0.02285 €/t.km., i.e. 68.55 €/barge.km.

Unit rail costs (C^R_{jk}) in €/t.km are given in [26] and are estimated using formula 27.

$$\frac{0.59325 + 0.01900 s_{jk} + 0.001804 \frac{s_{jk}}{ln(s_{jk})}}{s_{jk}} \tag{27}$$

s_{jk} refers to the rail distance between terminals j and k. This function has been obtained by considering several hypotheses such as an average load factor of 0.5 per train [22]; [23]. Please refer to [26] for the detailed explanation of the numerical values of other parameters.

Transshipment costs (C^T_j) are based on [25] and are assumed, for both rail and IWW, equal to 2.8 €/t [25].

Emission functions are based on the NTM methodology. They are obtained from the work of [22]; [23] for road, rail and water transportation.

Unit road transport emissions (E^L_{im}) for long-haul travels and for collection/distribution travels (E^P_{ij}) are expressed in kg of CO_2/t.km and are determined by expression 28.

$$\frac{\gamma C^F E^F}{K^T \lambda} \tag{28}$$

K^T is the maximum capacity of one truck and λ is the load factor of the truck. Emissions also depend on the fuel consumption (C^F), on a terrain factor (γ) which reflects the different consumption levels over hilly or flat terrains, and on the fuel emissions (E^F). It is assumed that a single truck transports two twenty feet equivalent units (2 TEU). Since a TEU contains on average 12 tonnes of freight, K^T is thus equal to 24 tonnes. A load factor of 0.85 is considered for long-haul travels and 0.6 for short-haul travels [14]. Fuel consumption is assumed to be equal to 0.3399 l/km for long-haul travels and 0.4175 l/km for short-haul travels. A terrain factor of 1.05 is considered. Fuel emissions are taken as 2.621 kg of CO_2/l of fuel. The unit road emissions are thus computed as $2.7440 * 10^{-2}$ kg of CO2/t.km for long-haul travels and as $4.7886 * 10^{-2}$ kg of CO_2/t.km for collection/distribution travels.

Unit IWW emissions of a barge of size t (E^{tW}_{jk}) in kg of CO_2/barge.km are based on the NTM methodology developed in the paper of [23]. According to this methodology, unit IWW emissions are obtained using equation 29.

$$C^F E^F \tag{29}$$

Fuel consumption of 0.007 t/km and fuel emissions of 3,178 kg of CO_2/t are taken into account. Considering that a medium barge has a maximum capacity of 3,000 t, the unit IWW emissions for this barge size are thus equal to $7.145 * 10^{-3}$ kg of CO_2/t.km.

Unit rail emissions (E^{vR}_{jk}) of a train v, loaded with a predetermined amount of freight, are expressed in kg of CO_2/ton.km using equation 30 for electrical trains and equation 31 for diesel trains. Rail emissions are also based on the NTM methodology.

$$\frac{T\gamma E^E}{1000\lambda(1-L)\sqrt{g}} \tag{30}$$

$$\frac{T\gamma E^F}{10^6\lambda\sqrt{g}} \tag{31}$$

T stands for the energy consumption for a flat region. As for road transport, γ reflects the topography of the studied area. E^E represents the energy efficiency i.e. the quantity of CO_2 emissions required for producing one kWh. λ is the load factor of the train and L is a percentage representative of the energy loss, when transferring the energy from the power plant to the train. g is the gross weight of a full train. Finally, E^F stands for the amount of CO_2 released in the atmosphere for one unit of fuel burnt.

In this section, we assume that there is only one type of loaded train v. We consider a load factor of 0.5, a gross weight of the train of 1,371 tonnes and a topography factor equal to 1.25 ([22]; [23]). For electrical trains, the energy consumption for a flat region is assumed to be 540 Wh/km and the energy efficiency is set to 0.41 kg/kWh (average value for Europe). The energy loss factor is fixed to 0.1. For diesel trains, the fuel consumption factor is taken as 122.46 and the fuel emissions as 3,175 g of CO_2/kg of diesel consumed. Results of equations 30 and 31 are finally weighted by the average proportion of train technology in Europe for obtaining the emission ratio by t.km. 75.4% of the European rail network operates using electricity whereas 24.6% uses the diesel technology. This leads to unit rail emissions for an average train of $1.638 * 10^{-2}$ kg of CO_2/t.km.

Transshipment emissions at the terminal are based on [31]. They are estimated at 0.002 tonnes of CO_2/handling of a container with cranes.

In the following analysis, we assume that there is no storage at the terminal and that goods only have to be transshipped using cranes. Considering that a container contains on average 12 tonnes of freight [25], one determines the transshipment emissions (E^T_j) at the terminal as $1.67 * 10^{-4}$ t of CO_2/t of handled goods.

C Cost and emission functions of the nonlinear approach

Cost functions for road are still based on the work of [25] and [26]. Unit road operational costs for long-haul (C^L_{im}) and collection/distribution travels (C^P_{ij}) are determined as in the linear approach. Indeed, we neglect the potential economies of scale related to road transport since we consider that a truck either transports its TEUs or it does not travel.

In the literature, no general nonlinear formulation for IWW costs has been found, which was modelling IWW costs as a nonlinear function of the weight transported [37]. In order to remain coherent in the formulation of IWW functions, we modelled IWW economies of scale through the use of three different barge sizes, both for costs and emissions.

Unit IWW costs (C^{tW}_{jk}) of a barge of size t are computed as in the linear approach. In this first scenario, only one average medium barge is taken into account whereas three sizes of barges are considered in the current nonlinear approach, which leads to three different costs. [39], based on data from Voies Navigables de France, assumes that the unit costs of barges vary between 0.0076 (large barges) and 0.0381 (small barges) €/t.km. One can therefore deduct that the cost for an average medium barge is 0.02285 €/t.km.

Small ships are represented by the ECMT class IV boats, i.e. Johann Welker type (maximum capacity of 1,500 t). Medium barges correspond to the ECMT class Va, i.e. large Rhine ships (maximum capacity of 3,000 t). Finally large barges are assumed to be part of the ECMT class VIIb, i.e. pushed convoys (maximum capacity of 12,000 t). These specific vessels' sizes have been chosen as reference for the representation of small, average and large barges because they correspond to the most often IWW capacities encountered in Belgium. Therefore, we assume a barge capacity of 1,500, 3,000 and 12,000 t, respectively for small, medium and large size barges. Taking into account these capacities, we determine that unit IWW costs are around 57 €/barge.km for small ships, 69 €/barge.km for medium ships and 91 €/barge.km for large ships.

Transshipment costs (E^T_j) are valued as in the linear approach.

Unit rail operational costs (C^R_{jk}) in €/t.km come from [25] and are determined by equation 32.

$$\frac{\sqrt{2}}{2X^i_{jk}s_{jk}}0.58(gs_{jk})^{0.74}\left[\frac{X^i_{jk}T(\alpha_{b1}+\alpha_{b2})}{0.58(gs_{jk})^{0.74}+0.57(gs_{jk})^{0.6894}}\right]^{0.5} \tag{32}$$

X^i_{jk} refers to the amount of goods (in tonnes) that is really transported from origin node i and that passes though rail terminals j and k. s_{jk} represents the rail distance between terminals j and k. g is the gross weight of a full train and is equal to 1,371 tonnes [25]. Given the cost function formulation, it is to notice that an increase of the transported quantity X^i_{jk} leads to economies of scale and therefore to reduced average costs per tonne.kilometer. Rail costs thus take into account economies of scale related to the bundling of flows in terms of weight. Parameter T represents the network operating time. It is fixed and supposed equal to five days a week multiplied by 52 weeks a year, i.e. 6,240 hours. Finally, α_{b1} and α_{b2} stand for the unit cost of time per units in zones 1 and 2 and are assumed to be 0.028 €/hour.tonne.

Unit road transport emissions (E^L_{im}) for long-haul travels and for collection/distribution travels (E^P_{ij}) are expressed as in the linear approach. As for road costs, we neglect potential economies of scale in terms of emissions for road transport.

IWW emissions of a barge (E^{tW}_{jk}) in kg of CO2/barge.km are based on the NTM methodology. Three emission levels are considered for small, medium and large size barges, which reflects the potential economies of scale obtained when using larger vehicles, on different sizes of IWW.

As in the linear approach, medium barges are supposed to emit $7.145 * 10^{-3}$ kg of CO_2/t.km. We assume that small size barges have a unit emission rate 20% higher, while we consider that that large size boats generate 20% less emissions than medium barges. Knowing the capacities of each boat, we can deduct the values of emissions as 12.86 kg of CO_2/barge.km for small barges, 21.43 kg of CO_2/barge.km for medium barges, and 68.52 kg of CO_2/barge.km for large barges.

Unit rail emissions (E^{vR}_{jk}) are expressed in kg of CO_2/ton.km using equation 33 for electrical trains and 34 for diesel trains.

$$\frac{T\gamma E^E}{1000(1-L)\sqrt{W_{empty}+X^{vi}_{jk}}} \tag{33}$$

$$\frac{T\gamma E^F}{10^6\sqrt{W_{empty}+X^{vi}_{jk}}} \tag{34}$$

Compared to the linear approach, the load factor and the gross weight of the train have been replaced by W_{empty} and X^{vi}_{jk}. W_{empty} refers to the tare of the train, i.e. the weight of a train with no merchandise loaded on it. It is assumed equal to 903 tonnes ([25]; [26]). X^{vi}_{jk} is the net weight of freight transported by train v between terminals j and k. This amount is limited to the maximum capacity of one train (A) i.e. 468 tonnes ([25]; [26]).

Finally, transshipment emissions at the terminal (E^T_j) are valued exactly as in the linear approach.

The nonlinear functions presented here above are approximated using piecewise linear functions, to permit the use of linear programming solvers for the resolution of the model. The next paragraphs detail how this piecewise linearization is practically performed.

[25] states that one train a day, i.e. five trains a week, is the most common train frequency in many trans-European intermodal markets-corridors. One train a day is thus the unit chosen as the increment between two segments of the piecewise linear function for rail that approximates the nonlinear costs. Using this method thus allows cutting the function between the minimum and maximum flows, according to the benchmark situation.

The first segment of the function therefore contains the annual flows which correspond to zero trains a day until one train a day. The second segment focuses on the annual flows equivalent to one train until two trains a day. And the cut is iteratively continued, until reaching the last segment, which contains the additional capacity required for achieving the maximum flows value.

In this case study, the cost function is divided into seven segments. The first six ones are equal and their size corresponds to the annual flows transported if one train a day is used. The last segment of the function contains the annual flows corresponding to more than six trains a day.

Rail emissions are computed thanks to equations 33 and 34, respectively for electrical and diesel trains.

The specificity of these functions is that the value of X_{jk}^{vi}, the weight transported, cannot exceed the maximum amount transportable in a single train. The emissions generated are thus nonlinear with the weight transported inside a specific train. However, the total emissions generated by a flow equivalent to an integer number of trains are linear with the number of trains. In this work, we determine the different segments of the piecewise linear function using breakpoints equivalent to an integer multiple of trains. Since the economies of scale are developed inside a specific train and not from one train to another, the obtained piecewise linear function is thus simply linear.

In Belgium, in 2008 and 2009, around 80% of the travels were performed using electric locomotives whereas 20% of these travels were done with the help of diesel machines [18].

The nonlinear emissions functions for electrical and diesel trains are thus reduced to a linear emission value, based on an 80-20 repartition key.

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