

# Intermodal network design: a three-mode bi-objective model applied to the case of Belgium

Martine Mostert<sup>1</sup>  · An Caris<sup>2</sup> · Sabine Limbourg<sup>1</sup>

Published online: 12 January 2017  
© Springer Science+Business Media New York 2017

**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 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.

---

**Electronic supplementary material** The online version of this article (doi:[10.1007/s10696-016-9275-1](https://doi.org/10.1007/s10696-016-9275-1)) contains supplementary material, which is available to authorized users.

---

✉ Martine Mostert  
martine.mostert@ulg.ac.be

<sup>1</sup> QuantOM, HEC Management School, University of Liege, Rue Louvrex 14, 4000 Liège, Belgium

<sup>2</sup> Research Group Logistics, Hasselt University, Agoralaan Gebouw D, 3590 Diepenbeek, Belgium

**Keywords** Intermodal network design · Bi-objective · Nonlinear · Economies of scale · CO<sub>2</sub>

## 1 Introduction

One of the most negative impacts of transport on climate change is the release of CO<sub>2</sub> emissions. Road transport represents around 20% of the total carbon dioxide emissions in Europe (European Commission 2015b). 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 (European Commission 2011). 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 (United Nations 2001). For ensuring intermodal competitiveness both in terms of economic and environmental issues, it is of strategic importance to correctly locate intermodal terminals (Mostert and Limbourg 2016). 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 (Bontekoning et al. 2004; Mathisen and Sandberg Hanssen 2014) in the literature and an important part of research is concentrated on supporting the decision-making process (Macharis and Bontekoning 2004; Caris et al. 2008, 2013; SteadieSeifi et al. 2014).

In particular, network design problems have been addressed using several methodologies: agent-based models (Sirikijpanichkul et al. 2007), GIS-based models (Macharis and Pekin 2009; Macharis et al. 2010; Zhang et al. 2013; Meers and Macharis 2014) or mathematical programming models (Arnold et al. 2001, 2004; Racunica and Wynter 2005; Ishfaq and Sox 2011; Sørensen et al. 2012; Sørensen and Vanovermeire 2013; Lin et al. 2014; Bouchery and Fransoo 2015; Santos et al. 2015; Zhang et al. 2015).

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 (Arnold et al. 2004; Racunica and Wynter 2005; Ishfaq and Sox 2011; Sørensen et al. 2012; Ghane-Ezabadi and Vergara 2016). Some models focus on generalized costs of transport, including transport externalities (Zhang et al. 2013, 2015; Santos et al. 2015). Single-objective optimization can also be applied to emissions minimization or modal split maximization (Bouchery and Fransoo 2015). Few articles of bi-objective modeling are available in intermodal transport applications. Sørensen and Vanovermeire (2013) 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, Chen et al. (2013) 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 Ghane-Ezabadi and Vergara (2016), who develop a path-based formulation allowing the use of several modes of transport, and Zhang et al. (2015), 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 (Arnold et al. 2001, 2004; Racunica and Wynter 2005; Ishfaq and Sox 2011; Limbourg and Jourquin 2009; Sørensen et al. 2012; Santos et al. 2015). Some papers however include road, rail and inland waterway transport (Macharis and Pekin 2009; Macharis et al. 2010; Meers and Macharis 2014), 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 (Racunica and Wynter 2005; Ishfaq and Sox 2011; Ghane-Ezabadi and Vergara 2016) or at the intermodal terminal, during the transshipment process (Limbourg and Jourquin 2009; Zhang et al. 2013, 2015). 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<sub>2</sub> 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 Zhang et al. (2013), Meers and Macharis (2014), Bouchery and Fransoo (2015), Santos et al. (2015), and Zhang et al. (2015) are the most related to our research. Zhang et al. (2013, 2015) focus on bi-level optimization and consider CO<sub>2</sub> 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<sub>2</sub> emissions in terms of intermodal network design. In addition, Zhang et al. (2013, 2015) integrate economies of scale at the intermodal terminal, whereas we look at economies of scale during the long-haul intermodal transport. Meers and Macharis (2014) 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 Meers and Macharis (2014) only consider them implicitly. Bouchery and Fransoo (2015) locate a single terminal. Alternatively, this work focuses on the location of several terminals between many origin and destination nodes. Bouchery and Fransoo (2015) 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 Bouchery and Fransoo (2015) permit to select either road or intermodal transport. Our model is also subject to different constraints, not only related to demand satisfaction. Santos et al. (2015) 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<sub>2</sub> 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<sub>2</sub> 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 (Arnold et al. 2004; Limbourg and Jourquin 2009; Santos et al. 2015), 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 (Arnold et al. 2004; Racunica and Wynter 2005; Ishfaq and Sox 2011) using the hub location theory (Alumur and Kara 2008; Farahani et al. 2013), 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 (Lin et al. 2014).

The minimization of operational costs and CO<sub>2</sub> 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<sub>2</sub> 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 (European Commission 2015b), since heavy duty vehicles are responsible for 25% of road transport and 6% of total transport CO<sub>2</sub> emissions. CO<sub>2</sub> 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 km (t km), barge km (barge km) and tonnes (t).

## 2.1 Sets

$T$	Set of types of barges, according to their size, indexed by $t \in \{1, \dots, d\}$
$V$	Set of trains, indexed by $v \in \{1, \dots, f\}$
$N$	Node set consisting of $n$ demand nodes, indexed by $i, m \in \{1, \dots, n\}$
$H$	Existing and potential terminal (hub) set, ( $H \subseteq N$ ) consisting of $h$ nodes, indexed by $j, k \in \{1, \dots, h\}$
$N_0$	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)
$C_{im}^L$	Long-haul road transportation costs for travelling from node $i$ to node $m$ (in €/t km)
$C_{ij}^P$	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 <sub>2</sub> /t km)
$E_{ij}^P$	Collection/distribution road transportation emissions for travelling from node $i$ to terminal $j$ (in kg of CO <sub>2</sub> /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 <sub>2</sub> /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 <sub>2</sub> /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<sub>2</sub>/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)  $\forall i, m \in N$
- $X_{jk}^i$  Flows from node  $i$  firstly routed through origin rail terminal  $j$  and then through destination rail terminal  $k$  (in t)  $\forall i \in N, \forall j, k \in H_R$
- $X_{jk}^{iv}$  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)  $\forall v \in V, \forall i \in N, \forall j, k \in H_R$
- $Q_{km}^i$  Flows from origin  $i$  to destination  $m$  that are routed through rail destination terminal in  $k$  (in t)  $\forall i, m \in N, \forall k \in H_R$
- $F_{jk}^i$  Flows from node  $i$  firstly routed through origin IWW terminal  $j$  and then through destination IWW terminal  $k$  (in t)  $\forall i \in N, \forall j, k \in H_W$
- $V_{km}^i$  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

$$\begin{aligned}
 f_{costs} = & \sum_{i \in N} \sum_{m \in N} d_{im} C_{im}^L W_{im} \\
 & + \sum_{i \in N_0} C_i^T W_{im} + \sum_{m \in N_0} C_m^T W_{im} \\
 & + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} (d_{ij} C_{ij}^P + C_j^T) X_{jk}^i \\
 & + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} s_{jk} C_{jk}^R X_{jk}^i \\
 & + \sum_{i \in N} \sum_{k \in H_R} \sum_{m \in N} (d_{km} C_{km}^P + C_k^T) Q_{km}^i \\
 & + \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} (d_{ij} C_{ij}^P + C_j^T) F_{jk}^i \\
 & + \sum_{t \in T} \sum_{j \in H_W} \sum_{k \neq j \in H_W} l_{jk} C_{jk}^W M_t \\
 & + \sum_{i \in N} \sum_{k \in H_W} \sum_{m \in N} (d_{km} C_{km}^P + C_k^T) V_{km}^i
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 f_{emissions} = & \sum_{i \in N} \sum_{m \in N} d_{im} E_{im}^L W_{im} \\
 & + \sum_{i \in N_0} E_i^T W_{im} + \sum_{m \in N_0} E_m^T W_{im} \\
 & + \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} (d_{ij} E_{ij}^P + E_j^T) X_{jk}^i \\
 & + \sum_{v \in V} \sum_{i \in N} \sum_{j \in H_R} \sum_{k \neq j \in H_R} s_{jk} E_{jk}^{vR} X_{jk}^{vi} \\
 & + \sum_{i \in N} \sum_{k \in H_R} \sum_{m \in N} (d_{km} E_{km}^P + E_k^T) Q_{km}^i \\
 & + \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} (d_{ij} E_{ij}^P + E_j^T) F_{jk}^i \\
 & + \sum_{t \in T} \sum_{j \in H_W} \sum_{k \neq j \in H_W} l_{jk} E_{jk}^{tW} M_t \\
 & + \sum_{i \in N} \sum_{k \in H_W} \sum_{m \in N} (d_{km} E_{km}^P + E_k^T) V_{km}^i
 \end{aligned} \tag{2}$$

2.5 Subject to

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

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

$$D_{im} = W_{im} + \sum_{k \in H_R} Q_{km}^i + \sum_{k \in H_W} V_{km}^i \quad \forall i, m \in N \tag{5}$$

$$\begin{aligned}
 \sum_{m \in N} D_{im} = & \sum_{m \in N} W_{im} \\
 & + \sum_{j, k \in H_R} X_{jk}^i + \sum_{j, k \in H_W} F_{jk}^i \quad \forall i \in N
 \end{aligned} \tag{6}$$

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

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

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



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

$$\sum_{j \in H_R} X_{jk}^i = \sum_{m \in N} Q_{km}^i \quad \forall i \in N, \forall k \in H_R \tag{11}$$

$$\sum_{j \in H_W} F_{jk}^i = \sum_{m \in N} V_{km}^i \quad \forall i \in N, \forall k \in H_W \tag{12}$$

$$\sum_{i \in T} M_i K_i \geq \sum_{i \in N} \sum_{j \in H_W} \sum_{k \neq j \in H_W} F_{jk}^i \tag{13}$$

$$X_{jk}^i = \sum_{v \in V} X_{jk}^{vi} \quad \forall i \in N, \forall j, k \in H_R \tag{14}$$

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

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

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

$$Q_{km}^i \geq 0 \quad \forall i, m \in N, \forall k \in H_R \tag{18}$$

$$F_{jk}^i \geq 0 \quad \forall i \in N, \forall j, k \in H_W \tag{19}$$

$$V_{km}^i \geq 0 \quad \forall i, m \in N, \forall k \in H_W \tag{20}$$

$$y_k \in \{0, 1\} \quad \forall k \in H \tag{21}$$

Equations 1 and 2 respectively stand for the total operational costs and emissions of transport companies. These equations are divided into: (1) door-to-door road costs/emissions, (2) transshipment costs/emissions between sea and road, (3) railroad intermodal costs/emissions and (4) IWW-road intermodal costs/emissions. Elements (3) and (4) 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 7–10 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 16–20 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  $\varepsilon$ -constraint resolution technique of Chankong and Haimes (1983). 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  $\varepsilon$  (Rangaiah 2009). In this study, the CO<sub>2</sub> 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 (Belotti et al. 2013; Chankong and Haimes 1983; Jeroslow and Lowe 1984; Kimms 2006; Rangaiah 2009).

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 Triligiport 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 (European Commission 2015a), 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 (Macharis and Pekin 2009; Macharis et al. 2010; Santos et al. 2015), and to evaluate if opening additional intermodal terminals is still desirable from the terminal operator's perspective (Meers and Macharis 2014).

Demand containerized data consists in road, rail and IWW flows and originates from Carreira et al. (2012). 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 (Carreira et al. 2012) and IWW (Promotie Binnenvaart Vlaanderen 2015) 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 Zeebrugge 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 (2011).

### 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 (European Commission 2001; Hoen et al. 2010; Hoen et al. 2014; Janic 2007; Janic 2008; te Loo 2009; PWC 2003). Figure 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.

The Pareto front shows that emphasizing more environmentally friendly transport implies additional financial means. Table 1 provides the relative optimal objective

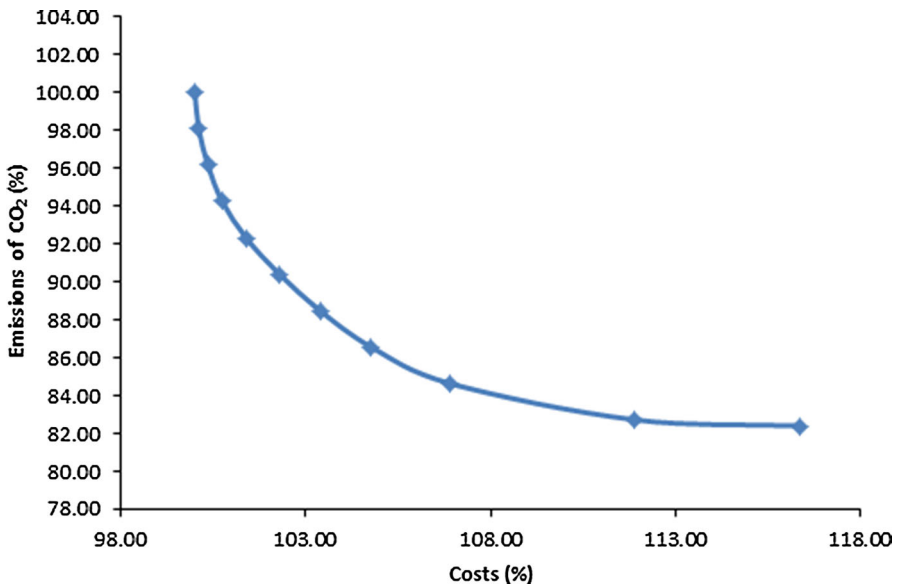


Fig. 1 Pareto front for the bi-objective model in the linear case

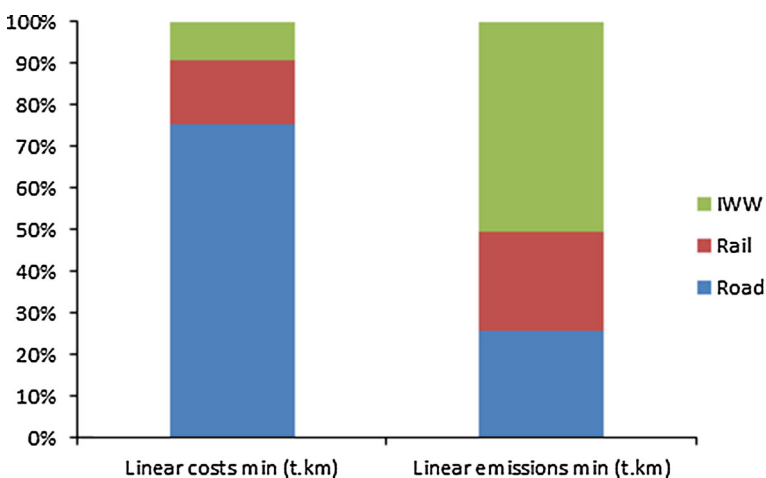
**Table 1** Results of the optimal costs and emissions minimization cases

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

values, the flow distribution values and the number of located terminals, under the two extreme points of the Pareto curve.

Figure 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 (Eurostat 2015). 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 (Central Commission for the Navigation of the Rhine 2014). The actual modal split is also influenced by the awarded subsidies (Santos et al. 2015), 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 origin-destination pair. For origin-destination pairs with volumes, the modal choice greatly influences the general market share distribution in t.km.

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

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.

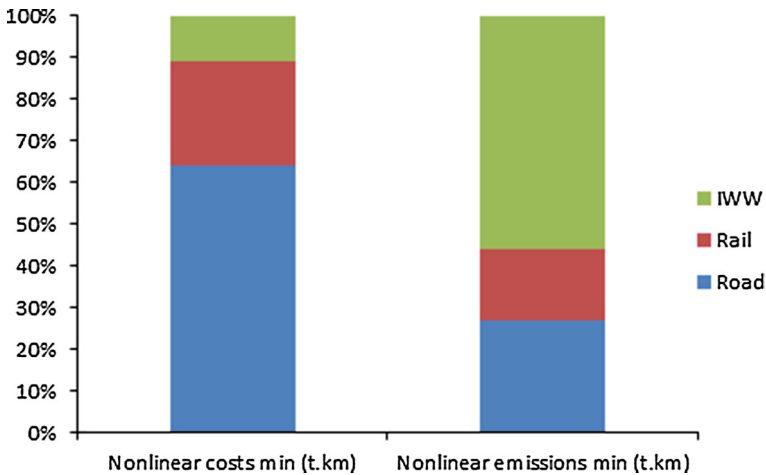
The application of the linear model to the Belgian case study shows that the cost effort for achieving a same amount of reduction of CO<sub>2</sub> emissions becomes larger as one approaches the emissions optimality scenario. The chosen policy (costs or emissions minimization) leads to the location of 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 is described in online Appendix C (Eurostat 2014; Janic 2007; Janic 2008; Mostert and Limbourg 2016; PWC 2003). 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.

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

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



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

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 advises the use of intermodal transport. This result shows that, to the contrary of what is recommended by the European Commission in its White Paper (European Commission 2011), 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 Bouchery and Fransoo (2015), 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 Mostert and Limbourg (2016). The conclusions of Janic (2008), 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 Zhang et al. (2013, 2015), our results also show the strong link between the terminal network configuration and the amount of CO<sub>2</sub> 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<sup>2</sup> for road, 2 \* 88<sup>3</sup> for intermodal rail, and 2 \* 88<sup>3</sup> for intermodal IWW transport. As Ernst and Krishnamoorthy (1998), 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 (Farahani et al. 2013), 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 s. 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 s. 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 1912 and 14,069 s. The average time for solving one point of the Pareto curve is 7339 s. 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 s.

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. Sørensen et al. 2012) 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 the pre- and post-haulage stages of intermodal transport.



**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

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 (Macharis and Pekin 2009). 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.

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

**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

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 (European Commission 2011). 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<sub>2</sub> 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.

**Acknowledgements** Martine Mostert acknowledges the financial support of FRS-FNRS (Fonds de la Recherche Scientifique). The authors thank Annick Sartenaer and Thibaut Lust for their valuable advice. The authors are also grateful to the two anonymous reviewers who provided constructive comments which definitely improved the paper. The project leading to the presented results was partially supported by the Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office, Comex, Grant P7/36. The paper, however, only expresses the view of the authors.

## References

- Alumur S, Kara BY (2008) Network hub location problems: the state of the art. *Eur J Oper Res* 190(1):1–21. doi:10.1016/j.ejor.2007.06.008. <http://www.sciencedirect.com/science/article/pii/S0377221707005577>
- Arnold P, Peeters D, Thomas I, Marchand H (2001) Pour une localisation optimale des centres de transbordement intermodaux entre réseaux de transport: formulation et extensions. *Can Geogr/Lé Gographe canadien* 45(3):427–436. doi:10.1111/j.1541-0064.2001.tb01192.x
- Arnold P, Peeters D, Thomas I (2004) Modelling a rail/road intermodal transportation system. *Transp Res Part E Logist Transp Rev* 40(3):255–270. doi:10.1016/j.tre.2003.08.005. <http://www.sciencedirect.com/science/article/pii/S1366554503000723>
- Belotti P, Kirches C, Leyffer S, Linderoth J, Luedtke J, Mahajan A (2013) Mixed-integer nonlinear optimization. *Acta Numer* 22:1–131. doi:10.1017/S0962492913000032. [http://journals.cambridge.org/article\\_S0962492913000032](http://journals.cambridge.org/article_S0962492913000032)
- Bontekoning Y, Macharis C, Trip J (2004) Is a new applied transportation research field emerging? A review of intermodal railtruck freight transport literature. *Transp Res Part A Policy Pract* 38(1):1–34. doi:10.1016/j.tra.2003.06.001. <http://www.sciencedirect.com/science/article/pii/S0965856403000740>
- Bouchery Y, Fransoo J (2015) Cost, carbon emissions and modal shift in intermodal network design decisions. *Int J Prod Econ* 164:388–399. doi:10.1016/j.ijpe.2014.11.017. <http://www.sciencedirect.com/science/article/pii/S092552731400379X>

- Caris A, Macharis C, Janssens GK (2008) Planning problems in intermodal freight transport: accomplishments and prospects. *Transp Plan Technol* 31(3):277–302. doi:[10.1080/03081060802086397](https://doi.org/10.1080/03081060802086397)
- Caris A, Macharis C, Janssens GK (2013) Decision support in intermodal transport: a new research agenda. *Comput Ind* 64(2):105–112. doi:[10.1016/j.compind.2012.12.001](https://doi.org/10.1016/j.compind.2012.12.001). <http://www.sciencedirect.com/science/article/pii/S0166361512002047>. Decision support for intermodal transport
- Carreira J, Santos BF, Limbourg S (2012) Inland intermodal freight transport modelling. In: 40th ETC—European transport conference, Glasgow, UK
- Central Commission for the Navigation of the Rhine (2014) Inland navigation in Europe market observation 2014. Tech. rep., CCNR, Strasbourg
- Chankong V, Haimes Y (1983) Multiobjective decision making: theory and methodology. North-Holland series in system science and engineering. North Holland. <https://books.google.be/books?id=Zlg-AQAAlAAJ>
- Chen G, Govindan K, Goliass MM (2013) Reducing truck emissions at container terminals in a low carbon economy: proposal of a queueing-based bi-objective model for optimizing truck arrival pattern. *Transp Res Part E Logist Transp Rev* 55:3–22. doi:[10.1016/j.tre.2013.03.008](https://doi.org/10.1016/j.tre.2013.03.008). <http://www.sciencedirect.com/science/article/pii/S1366554513000586>. Green shipping management
- Ernst AT, Krishnamoorthy M (1998) Exact and heuristic algorithms for the uncapacitated multiple allocation p-hub median problem. *Eur J Oper Res* 104(1):100–112. doi:[10.1016/S0377-2217\(96\)00340-2](https://doi.org/10.1016/S0377-2217(96)00340-2). <http://www.sciencedirect.com/science/article/pii/S0377221796003402>
- European Commission (2001) Real cost reduction of door-to-door intermodal transport RECORDIT. Tech. rep., European Commission, Directorate General DG VIIRTD, 5th Framework Programme, Brussels
- European Commission (2011) White paper: roadmap to a single European transport area—towards a competitive and resource efficient transport system. Tech. rep., COM, Brussels
- European Commission (2015a) Commission refers Belgium and Bulgaria to court and gives Sweden a final warning over poor air quality. [http://europa.eu/rapid/press-release\\_IP-15-5197\\_en.htm](http://europa.eu/rapid/press-release_IP-15-5197_en.htm)
- European Commission (2015b) Road transport: reducing CO<sub>2</sub> emissions from vehicles. [http://ec.europa.eu/clima/policies/transport/vehicles/index\\_en.htm](http://ec.europa.eu/clima/policies/transport/vehicles/index_en.htm)
- Eurostat (2014) Train movements, by type of vehicle and source of power. [http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=rail\\_tf\\_traveh&lang=en](http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=rail_tf_traveh&lang=en)
- Eurostat (2015) Modal split of freight transport. <http://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=tsdr220&language=en>
- Farahani RZ, Hekmatfar M, Arabani AB, Nikbaksh E (2013) Hub location problems: a review of models, classification, solution techniques, and applications. *Comput Ind Eng* 64(4):1096–1109. doi:[10.1016/j.cie.2013.01.012](https://doi.org/10.1016/j.cie.2013.01.012). <http://www.sciencedirect.com/science/article/pii/S0360835213000326>
- Ghane-Ezabadi M, Vergara HA (2016) Decomposition approach for integrated intermodal logistics network design. *Transp Res Part E Logist Transp Rev* 89:53–69. doi:[10.1016/j.tre.2016.02.009](https://doi.org/10.1016/j.tre.2016.02.009). <http://www.sciencedirect.com/science/article/pii/S1366554515300831>
- Hoer KMR, Tan T, Fransoo JC, van Houtum GJ (2010) Effect of carbon emission regulations on transport mode selection in supply chains. Tech. rep., Technische Universiteit Eindhoven, Eindhoven
- Hoer KMR, Tan T, Fransoo JC, van Houtum GJ (2014) Effect of carbon emission regulations on transport mode selection under stochastic demand. *Flex Serv Manuf J* 26(1):170–195. doi:[10.1007/s10696-012-9151-6](https://doi.org/10.1007/s10696-012-9151-6)
- Ishfaq R, Sox CR (2011) Hub location–allocation in intermodal logistic networks. *Eur J Oper Res* 210(2):213–230. doi:[10.1016/j.ejor.2010.09.017](https://doi.org/10.1016/j.ejor.2010.09.017). <http://www.sciencedirect.com/science/article/pii/S0377221710006156>
- Janic M (2007) Modelling the full costs of an intermodal and road freight transport network. *Transp Res Part D Transp Environ* 12(1):33–44. doi:[10.1016/j.trd.2006.10.004](https://doi.org/10.1016/j.trd.2006.10.004). <http://www.sciencedirect.com/science/article/pii/S1361920906000794>
- Janic M (2008) An assessment of the performance of the European long intermodal freight trains (lifts). *Transp Res Part A Policy Pract* 42(10):1326–1339. doi:[10.1016/j.tra.2008.06.008](https://doi.org/10.1016/j.tra.2008.06.008). <http://www.sciencedirect.com/science/article/pii/S0965856408001213>
- Jeroslow RG, Lowe JK (1984) Mathematical programming at Oberwolfach II, chap. Modelling with integer variables. Springer, Berlin, pp 167–184. doi:[10.1007/BFb0121015](https://doi.org/10.1007/BFb0121015)
- Kimms A (2006) Economies of scale in hub and spoke network design models: we have it all wrong. In: Morlock M, Schwindt C, Rautmann N, Zimmermann J (eds) Perspectives on operations research: essays in honor of Klaus Neumann. Gabler Publishing, Wiesbaden, pp 293–317

- Limbourg S, Jourquin B (2009) Optimal rail-road container terminal locations on the European network. *Transp Res Part E Logist Transp Rev* 45(4):551–563. doi:10.1016/j.tre.2008.12.003. <http://www.sciencedirect.com/science/article/pii/S136655450800149X>
- Lin CC, Chiang YI, Lin SW (2014) Efficient model and heuristic for the intermodal terminal location problem. *Comput Oper Res* 51:41–51. doi:10.1016/j.cor.2014.05.004. <http://www.sciencedirect.com/science/article/pii/S0305054814001336>
- Macharis C, Bontekoning YM (2004) Opportunities for OR in intermodal freight transport research: a review. *Eur J Oper Res* 153(2):400–416
- Macharis C, Pekin E (2009) Assessing policy measures for the stimulation of intermodal transport: a gis-based policy analysis. *J Transp Geogr* 17(6):500–508
- Macharis C, Van Hoeck E, Pekin E, Van Lier T (2010) A decision analysis framework for intermodal transport: comparing fuel price increases and the internalisation of external costs. *Transp Res Part A Policy Pract* 44(7):550–561
- Mathisen, TA, Sandberg Hanssen TE (2014) The academic literature on intermodal freight transport. *Transp Res Proc* 3:611 – 620. doi:10.1016/j.trpro.2014.10.040. <http://www.sciencedirect.com/science/article/pii/S2352146514002038>. 17th meeting of the EURO working group on transportation, EWGT2014, 2–4 July 2014, Sevilla, Spain
- Meers D, Macharis C (2014) Are additional intermodal terminals still desirable? An analysis for Belgium. *Eur J Transp Infrastruct Res* 14(2):178–196
- Mostert M, Limbourg S (2016) External costs as competitiveness factors for freight transport a state of the art. *Transp Rev*
- Promotie Binnenvaart Vlaanderen (2015) Periskal easy voyage planning. <http://pbv.periskal.com/#Pages/EasyVoyagePlanning.xaml>
- PWC (2003) Faire le choix du transport fluvial: l’avis des entreprises - Enquete voies navigables de france. Tech. rep., PWC
- Racunica I, Wynter L (2005) Optimal location of intermodal freight hubs. *Transp Res Part B Methodol* 39(5):453–477. doi:10.1016/j.tre.2004.07.001. <http://www.sciencedirect.com/science/article/pii/S0191261504000980>
- Rangaiah G (2009) Multi-objective optimization: techniques and applications in chemical engineering. Advances in process systems engineering. World Scientific. <https://books.google.be/books?id=kIRInZIUkzQC>
- Santos BF, Limbourg S, Carreira JS (2015) The impact of transport policies on railroad intermodal freight competitiveness the case of Belgium. *Transp Res Part D Transp Environ* 34:230–244. doi:10.1016/j.trd.2014.10.015. <http://www.sciencedirect.com/science/article/pii/S1361920914001564>
- Sirikijpanichkul A, Van Dam KH, Ferreira L, Lukszo Z (2007) Optimizing the location of intermodal freight hubs: an overview of the agent based modelling approach. *J Transp Syst Eng Inf Technol* 7(4):71–81
- Sörensen K, Vanovermeire C (2013) Bi-objective optimization of the intermodal terminal location problem as a policy-support tool. *Comput Ind* 64(2):128–135. doi:10.1016/j.compind.2012.10.012. <http://www.sciencedirect.com/science/article/pii/S0166361512001996>. Decision support for intermodal transport
- Sörensen K, Vanovermeire C, Busschaert S (2012) Efficient metaheuristics to solve the intermodal terminal location problem. *Comput Oper Res* 39(9):2079–2090. doi:10.1016/j.cor.2011.10.005. <http://www.sciencedirect.com/science/article/pii/S0305054811002930>
- StadieSeifi M, Dellaert N, Nuijten W, Van Woensel T, Raoufi R (2014) Multimodal freight transportation planning—a literature review. *Eur J Oper Res* 233(1):1–15. doi:10.1016/j.ejor.2013.06.055. <http://www.sciencedirect.com/science/article/pii/S0377221713005638>
- te Loo R (2009) A methodology for calculating CO<sub>2</sub> emissions from transport and an evaluation of the impact of European union emission regulations
- United Nations (2001) Terminology on combined transport. Tech. rep, United Nations, Geneva (Switzerland)
- Zhang M, Wiegmans B, Tavasszy L (2013) Optimization of multimodal networks including environmental costs: a model and findings for transport policy. *Comput Ind* 64(2):136–145. doi:10.1016/j.compind.2012.11.008. <http://www.sciencedirect.com/science/article/pii/S0166361512002011>. Decision support for intermodal transport

Zhang M, Janic M, Tavasszy L (2015) A freight transport optimization model for integrated network, service, and policy design. *Transp Res Part E Logist Transpo Rev* 77:61–76. doi:10.1016/j.tre.2015.02.013. <http://www.sciencedirect.com/science/article/pii/S1366554515000526>

**Martine Mostert** received a Master degree in Business Engineering with a major in Supply Chain Management from HEC Liege, the Management School of the University of Liege. She is now a PhD candidate at HEC Liege. Her research focuses on the modeling of freight transport networks. In particular, she is interested in developing decision support systems which account for the environmental impacts of transport. Her current research concentrates on intermodal freight transport.

**An Caris** was appointed in 2012 as Assistant Professor at the Faculty of Business Economics (BEW) of Hasselt University. She obtained her PhD in Applied Economics in 2010 and was first a postdoctoral research fellow of the Research Foundation - Flanders (FWO). Her research interest goes to the application of Operations Research (OR) techniques in the field of operations management and logistics. In her PhD thesis she focused on the competitiveness of intermodal transport making use of inland navigation. Currently she studies planning problems in warehouse operations, intermodal rail transport, collaborative logistics and healthcare logistics.

**Sabine Limbourg** is a Full Professor in logistics and transport at HEC Liege, the Management School of the University of Liege. Her research, strongly related to European transport policy for sustainable development, has led to the improvement of decision support systems for freight transportation planning. It focuses on establishing links between advanced operations management and the needs of both enterprises and communities. She is also involved in several multidisciplinary research projects; her main expertise is in facility location, traffic assignment problems, intermodal transport, optimization and loading constraints.