A three-mode bi-objective location model under economies of scale for intermodal transport

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Abstract

Intermodal transport is an efficient solution for reducing greenhouse gases of freight transport but it requires intermodal terminals, where the transfer between modes can occur. The location of these terminals is a key factor for achieving economic and environmental competitiveness. A bi-objective model for the intermodal terminal location-allocation problem is developed. The focus is on road and on intermodal rail and inland waterway transportation. Operational costs and CO_2 emissions are minimized, with the opportunity to integrate intermodal economies of scale. Intermodal global performances are assessed on the Belgian case study. Results show that intermodal inland waterway transport has to be preferred for ensuring better environmental performances.

Introduction

European authorities encourage the transfer of freight flows from road to more environmentally friendly modes of transport such as inland waterways (IWW) or rail (European Commission, 2011). The development of intermodal transport is a solution for achieving this modal transfer. Intermodal transport is defined as the transport of goods using two or more modes, in the same loading unit, without handling of the goods themselves (United Nations, 2001). The main benefits of intermodal transport, in terms of costs or externalities, are achieved on the long-haul travel, by the use of more environmentally friendly modes, such as rail or IWW. The location of intermodal terminals is thus of strategic importance in terms of competitiveness with door-to-door transport. Indeed, good locations of intermodal terminals improve the flow consolidation process, which leads to economies of scale on the travel performed by rail or IWW.

This research presents an innovative bi-objective location-allocation mathematical model which focuses on the optimization of operational costs and CO_2 emissions of transport. Costs and emissions minimization mainly refers to energy optimization. However some diverging factors between both functions are expected, such as lower repair and maintenance costs for road than for rail, but higher emissions for road than for rail. The possible opposition between costs and emissions can lead to different decisions. This is why both functions are integrated in a multi-objective optimization model. The considered perspective is the one of transportation companies.

The specificity of the model is to analyze the network design by integrating three different modes of transport i.e. road, intermodal using rail and intermodal using IWW transport. Another contribution is to allow for taking into account economies of scale of intermodal transport by using nonlinear cost and emission functions, instead of classically considering a discount factor on the long-haul travel.

Literature review

Intermodal transportation has been subject to a wide variety of research perspectives. Bontekoning et al. (2004) analyze 92 publications, identify the main research directions and provide future research outlook for railroad intermodal transport.

Our research falls within the research area of intermodal network design. The basic approach of such models consists in minimizing total operational costs of the network, subject to a certain number of constraints. Ishfaq and Sox (2011) develop a model based on the hub location theory and extend the related literature by applying the multiple-allocation *p*-hub median approach to intermodal rail transport. The authors minimize transportation costs between origin and destination nodes as well as terminal fixed opening costs. As the size of the problem may increase very quickly for larger networks, Sörensen et al (2012) develop two metaheuristic approaches for solving an integer programming model based on the work Arnold et al. (2001). Sörensen and Vanovermeire (2013) tackle the intermodal terminal location problem from a bi-objective point of view, minimizing transportation costs for the users of the terminal network and dealing with location costs minimization for the terminal operators. Zhang et al. (2013) develop a GIS-based model for the optimization of multimodal multi-commodity freight terminal networks systems. The authors propose a bi-level model which minimizes both system generalized costs and CO_2 emissions under different CO_2 prices. Meers and Macharis (2014) study the potential benefit of implementing additional railroad and barge-road intermodal terminals in Belgium. Based on a GIS-approach, they determine from the terminal operator’s perspective at which locations additional terminals should be built.

Model

The developed mathematical model has the objective to minimize both operational costs and CO_2 emissions. It is thus bi-objective. The major decision variables relate to (i) binary variables which determine if a terminal has to be located in a specific region or not and to (ii) variables representing the quantities of flows that are sent either by road, intermodal using rail or intermodal using IWW transport.

The most important constraints of the model are detailed hereafter. The program ensures that a maximum of *p* terminals can be located. This reflects the fact 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. The already existing terminals (sea port and intermodal terminal abroad) have to be considered as open. Some constraints ensure 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. It is also stated that no flow can pass through an intermodal terminal if this terminal is not open. Typical flow conservation constraints for rail and IWW transport are also included. We ensure that the number of available barges of a specific type is sufficient for satisfying the demand transported by this specific type using IWW. Finally, flow conservation between road transport by truck and rail transport by train, as well as train capacity restrictions are also guaranteed.

Methodology

One of the principal characteristics of the problem is to be bi-objective. The ε-constraint method of Chankong and Haimes (1983) is used to solve the model. The idea behind this method is to transform a multi-objective problem into single-objective optimization. Only one function is kept as the objective to optimize, and the other functions are taken as constraints being less or equal to a certain epsilon value. In this research, costs are taken as the objective to minimize, while emissions are considered in the constraints. The values of epsilon, related to the CO_2 emissions, are iteratively varied in order to generate the Pareto optimal solutions, i.e. the solutions for which none of the objective can be improved, without worsening the value of the other.

The costs and emissions functions originate from PWC (2003), Janic (2007, 2008), te Loo (2009) and Hoen et al. (2010, 2014).

The paper compares the bi-objective results of two approaches: (i) linear modeling without considering economies of scale of intermodal transport and (ii) non-linear modeling considering economies of scale.

The linear modeling uses costs and emissions functions that are linear with the number of tonnes or tonnes-kilometers performed. The model thus refers to mixed integer linear programming and is solved using the linear commercial solver CPLEX.

The nonlinear approach uses nonlinear costs and emissions functions for representing the economies of scale of intermodal transport. These functions have the form of square roots and are approximated by piecewise linear functions. The model can then be solved using a linear commercial solver such as CPLEX. The modeling of piecewise linear functions goes through the use of so called SOS2 (Special Ordered Sets of type 2) variables. The idea behind this formulation is that any *x*-value or *y*-value of a piecewise linear function can be expressed as the convex combination of the two breakpoints of the segment of the piecewise linear function, in which it lies. Additional SOS2 variables, lying between 0 and 1 are thus used for practically representing the formulation of the convex combination of the breakpoints (or their images). A set of variables is said to be SOS2 if at mot two of its variables are nonzero, and that these nonzero variables are adjacent.

We apply the model to the Belgian case-study. Flow exchanges inside Belgium and flow interactions between Belgium and its neighboring countries are considered. The already existing sea terminals inside Belgium and intermodal terminals abroad are taken into account. The use of intermodal transport is often recommended on medium and long distances. Nevertheless we find it interesting to analyze how the modal split between road-only and intermodal transport behaves on short distances. Belgium, thanks to its reduced geographical area, is therefore a good case-study on which the developed model can be applied. In addition, the important exchange of flows between Belgium and its neighboring countries also allows the analysis on longer distances.

Results

For both approaches, it has been decided to differentiate between long-haul and short-haul road costs and emissions. Indeed, long haul travels allow for economies of distance and thus provide competitive advantages. The limit between short-haul and long-haul travel has been fixed to 300 km. This seems to be the accepted distance by the European Commission (2011). Most of the internal

Belgian road flows are thus short-haul travels. A maximum of 15 rail and IWW terminals can be located by the model.

Linear

Whatever the cost-emission pair of the Pareto front, 15 terminals are always located by the model. This means that intermodal transport must be part of the solution for obtaining both optimal costs and emissions.

The flow repartition of the extreme case of the Pareto curve, where costs are minimized, without taking into account any constraints related to emissions, is as follows: 69% for road, 29% for rail and 2% for IWW. The other extreme case, where emissions are minimized, without taking into account any constraints related to costs, has the following flow repartition: 61% for road, 11% for rail and 28% for IWW.

Intermodal rail transport is favored in the costs minimization case, while intermodal IWW transport is more dominant in the emissions minimization case. For costs minimization, 14 rail and 1 IWW terminals are located, whereas 6 rail and 9 IWW terminals are chosen for emissions minimization. This result is coherent with the flow distribution described previously. It means that, for obtaining better results from the environmental point of view, more IWW terminals have to be located. Even if the type of terminal may change from costs to emissions minimization, it is important to notice that the terminal locations mainly remain the same.

The predominance of rail transport under costs minimization can be explained by the used cost functions. Indeed, rail unit costs vary between 0.019 and 0.025€/t.km, depending on the distance traveled, whereas IWW costs are fixed to 0.02285 €/t.km, whatever the distance value. Already for distances greater than 200 km, rail transport becomes more competitive than IWW transport. In addition, there are not as many IWW as rail potential locations for terminals, which leads to increased performed distances using barges rather than using trains. This is again in disfavor of IWW transport.

Under emissions minimization, the switch to more IWW transport can also be explained by the used emission functions. Indeed, unit IWW emissions are fixed to $7.145 * 10^{-3}$ kg/t.km, whereas rail transport has emissions of $1.638 * 10^{-2}$ kg of CO_2/t.km, i.e. twice as much as IWW transport. Even if the distance by barge is longer than the distance by train, the small unit IWW emissions can compensate for the larger distances.

The predominance of road for both costs and emissions minimization is explained by the absence of transshipment costs and emissions for this particular mode, as well as by shorter door-to-door distances than the ones that should be achieved using a train or a barge.

Nonlinear

The nonlinear part of the model is still under a test phase. We expect to give the first results of this section by the conference.

Conclusions

This research presents a new bi-objective location-allocation model for intermodal transport. Three modes are considered in the approach and the economies of scale of intermodal transport can be taken into account. The focus is on the minimization of both costs and CO_2 emissions, for measuring the economic and environmental impact of transport. Results tend to show that, whatever the objective of costs or emissions minimization, intermodal transport must be part of the solution. However, the market share of intermodal IWW transport has to be increased, in relation to road and intermodal rail transport, for achieving better environmental performances.

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