A bilevel model for network design and pricing based on a level-of-service assessment

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Abstract

Within a wide view to stimulate intermodal transport, this paper is devoted to the examination of the intrinsically related problems of designing freight carrying services and determining their associated prices as observed by the shipper firms. A path-based multicommodity formulation is developed for a medium-term planning horizon, from the perspective of an intermodal operator. In the quest of incorporating nonprice attributes, two approaches are proposed to depict a realistic assessment of the service quality. First, frequency delay constraints are added to the upper level problem. Second, based on a random utility model, behavioural concepts are integrated in the expression of the lower level as a logistics costs minimization problem. Exact tests are invoked on real-world instances, demonstrating the capability of the presented approaches of reaching reasonable results within acceptable computation times and optimality gaps. The broader level-of-service perspective imposes additional costs on the service providers, although to a lesser extent on long-distance freight corridors, as indicated by the computed market share and net profit. Further experiments are conducted to test the impact of certain transport management instruments (e.g. subsidies and service capacities) on the modal split, as well as to assess the intermodality's future based on a scenario analysis methodology.

Keywords— bilevel programming; network design; network pricing; discrete choice analysis; intermodal transport

Introduction

Pricing decisions are among the most crucial issues that contribute to the position of a certain product or service. In order to maximize profitability through pricing, the decision maker opts to efficiently handle the tradeoff between increasing the prices to break even and generate a profit, and keeping the service economically appealing to the target customers (Phillips (2005)). The key to successfully achieve this balance rests upon an accurate knowledge of the

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underlying services' costs with respect to their offered level, vis-à-vis the market situation in terms of the customers' alternative options. In the context of freight transport services, this stream of problems is particularly relevant in the rise of reduced policy interventions (e.g., deregulation, privatisation, etc.) and the resulting consequences for many actors to adopt competitive *"market-survival"* strategies (Friedlaender and Spady (1981)). At a tactical planning horizon, freight service providers often find themselves in the position of devising services' prices for competitive contract terms along with designing their respective key schedules, and routes where applicable, bearing the challenging prospect of achieving their economic and service goals. This is specially relevant for rail-based freight transport, where operators are typically required to make months-long slots' requests from the infrastructure managers, in light of the expected demands of their customer shippers; see for instance the Network Reference document by Infrabel (2016) in Belgium for slots allocation policies. Other related system examples could include trucking and container shipping lines.

In this paper, we jointly address the intertwined tactical questions of service network design and pricing, from the perspective of a freight transport operator. In the context of the BRAIN-TRansversal Assessment of Intermodal New Strategies (BRAIN-TRAINS (2014)) project, this research is initially motivated by an application to help promote *intermodal transport*. As a transport scheme relying on modes for the long haul with less externalities and high load factors, it is regarded as both an ecological choice and one that promises potential economies of scale (Kreutzberger (2003); Kreutzberger et al. (2003); Mostert and Limbourg (2016)). Nevertheless, even in the presence of supporting political incentives (European Commission (2011)), there is a great imbalance in modal split on land with 71.3% of the EU freight transport still taking place via road (European Commission (2016a)). Intermodal transport competitiveness, and modal choice for that matter, is found to be greatly sensitive to the determination of the right service tariffs (Bontekoning et al. (2004)): an issue identified as both a significant and probable weakness in the face intermodality's economic success (Troch et al. (2015)), yet received little attention in the scientific literature (Caris et al. (2013); Tawfik and Limbourg (2018)).

We discuss a bilevel model, where the main decision maker (a leader) is portrayed, at the upper level, as a typical intermodal service provider seeking to maximize his profits by setting the services' tariffs and selecting their subsequent operating frequencies to construct feasible itineraries. At the lower level, the shippers' (followers') reaction to the leader's strategies is depicted within a logistics costs assessment reasoning. The market is assumed to consist of small customer shippers seeking to benefit from freight consolidation by choosing to send their demands between the proposed intermodal itineraries and an always available trucking alternative, with the possibility of *splitting* their volumes over several paths. The factor of the shippers' price negotiation power is thus eliminated in our analysis. Two linearised mixed-integer problem (MIP) formulations, presenting different styles to model the level-of-service attributes, are developed and invoked on real-world instances. More precisely, we opt to set service quality standards once by imposing frequency delay constraints, and once by integrating a statistically estimated logistics disutility in the shippers' reaction. Several computational tests are conducted on real-world instances using the solver CPLEX, with the aim of comparing the results obtained by the proposed approaches and deriving managerial insights with respect to offering rail subsidies, varying its capacity and assessing the position of intermodality in a best-case scenario. To summarize, the main contribution of this work is two-fold: (i) methodologically, to extend bilevel design and pricing models in order to account for nonprice attributes as well as a generalized representation of freight service networks and and (ii) practically, to use the relevant developed framework to answer policy-related questions concerning the future development of intermodal transport in Europe, taking Belgium as a point of interest.

The remainder of the paper is organized as follows. In section 1, we provide a comprehensive review of the state of the literature in what concerns the topics of transport service design and pricing, and the related application of the bilevel programming paradigm. In section 2, we present a bilevel mathematical formulation of the joint design and pricing problem, underlying necessary reformulations and enhancements. The model is further extended in section 3 to include the logistics service assessment of the non-price aspects through the means of the two above mentioned approaches. The computational results and related conclusions are discussed in section 4, while closing remarks are given in the last section along with potential future perspectives.

1 Literature review and problem statement

Despite being intrinsically related, the issues of service design and pricing have been mostly regarded separately in tactical optimization approaches. Crainic (2000) presents a generic framework for service network design in freight transport. A state-of-the-art review is conducted with the aim to bridge the gap between modelling efforts in service network design tailored to specific transport modes and the mathematical programming developments in traditional network design formulations. Following a functionality-based taxonomy, equivalent arc- and path-based models are analysed, together with a discussion of the possible representations of the service performance and the time dimension. A more recent review of service network design formulations incorporating different decisions, such as services' frequency, mode and routing, is considered by Wieberneit (2008).

In the parallel topic of service pricing, however, the *bilevel programming* paradigm has provided a suitable framework to depict this type of problems within a hierarchical setting. Bilevel programs, introduced by Bracken and McGill (1973), give the mathematical programming formulation of the (static) Stackelberg game-theoretical concept (Stackelberg (1952)), where a subset of the variables is constrained to assume the optimal value of a second optimization problem, while the latter problem is parametrized by the former's remaining variables. In the current context, the problem is represented as follows; a freight carrier anticipates, within his pricing strategy, the reactions of the shippers to his offer and that of the competition, and decides accordingly on the prices that maximize his gain. Bilevel pricing formulations on transport networks were first introduced by Labbé et al. (1998), where, at the upper level, a highway authority seeks revenue-maximizing tolls over a subset of links, while, at the lower level, the travellers choose the cheapest paths considering the sum of the tolls and fixed costs. This work has been extended along the freight-tariff setting direction in Brotcorne et al. (2000) and Brotcorne et al. (2001), where the lower level subsumes the structure of a transshipment problem for the single- and multiple- commodity network cases respectively.

It is worth mentioning the contributions along the related research line combining the revenue aspect of the day-to-day logistics activities with operations planning. According to Kimes (1989), Revenue (or Yield) Management

(RM) can be commonly defined as “a method which can help a firm sell the right inventory unit to the right type of customer, at the right time, and for the right price”. Following its success in the airline industry, RM has been gaining importance for other applications involving distinct service's attributes and capacity utilization requirements. To name a few, integrated pricing and capacity management has been studied in Crevier et al. (2012), Liu and Yang (2015) and Wang et al. (2016) for the rail freight, container sea-rail and intermodal barge transport respectively. Nevertheless, only few works, to our knowledge, addressed the simultaneous consideration of the network design and the service tariffs to be applied, from a medium-term decision horizon. An intermodal service pricing and operations planning is tackled by Li and Tayur (2005) with the perspective of satisfying service quality constraints and maximizing profits. An alternative framework to bilevel programming is considered for the pricing part; using a density function on each market, the demands are modelled based on marketing research and reservation prices data. A mathematical program with a concave objective function is then developed, for the case of two service classes. A stated limitation of the proposed approach is the complexity to obtain the demand (and price) function through analytical methods, when the number of customer or product classes becomes larger. The authors acknowledge the necessity to investigate numerical solution procedures in that case.

Brotcorne et al. (2008) provide a significant contribution to the subject by presenting a generic mixed-integer bilevel formulation for the joint design and pricing problem on transport networks, with an application to the telecommunication industry. The authors consider a profit-maximization problem at the upper level by simultaneously determining the connections to be opened and the tariffs assigned to them, whereas, at the lower level, the network users select the shortest paths joining their origins and destinations. Interesting results specific to this class of problems are discussed with respect to moving constraints involving variables from both levels, and the obtained structure of the model is utilized to design a solution algorithm based on Lagrangean relaxation.

A joint pricing and design problem is also studied by Ypsilantis (2016) from the perspective of maritime container terminal operating companies, currently acting as network operators. This same study is partially documented as well by Ypsilantis and Zuidwijk (2013). The considered decisions are three-fold: selection of inland terminals to act as extended gates, capacities of the corridors and the prices of the transport services over the network. A bilevel programming model is developed with a profit maximization objective. The model is adapted to multimodal networks by formulating frequency dependent service times and accounting for economies of scale. The customers' decision, always provided with an all-road alternative, is anticipated by minimizing their system costs at the lower level and expressing their required service level in the constraints. A heuristic method is designed for a realistic case study and produces near-optimal solutions in a reasonable time.

Departing from the initial framework in Brotcorne et al. (2008), we seek to add to the body of literature by presenting a joint bilevel service network design and pricing model, essentially applicable, however not limited, to an intermodal freight transport case. We study a path-based multicommodity formulation, akin to the service network problem discussed by Crainic (2000), considering capacitated services and integer frequency variables, as opposed to the simple open/close decisions. Arc-based pricing is chosen, as opposed to path-based pricing, as it represents a more general and challenging network case. In path-based pricing, the tolls are to be set based on each commodity's case individually, as paths could be priced differently for each commodity. Whereas, in arc-based pricing, tolls should be set uniformly, allowing for a portrayal of the interaction between the commodities.

The notion of a *service* depicts a transport connection between two physical points, using a certain mode with a maximum capacity. The transport operator decides on the frequencies of the offered services and their selling prices and seeks to achieve high load factors by bundling as much shipping demands as possible. The notion of an *itinerary*, on the other hand, will be used all along to represent the routing of the shipping demands through the network, where, for each demand, an itinerary is formed of a sequence of services that delivers the demand from its point of origin to its point of destination. On the (intermodal) transport operator's side, the costs - represented in a fixed and a variable component - depict the costs relative to acquiring the necessary slots from the infrastructure managers and operating the transport connections, thus reflecting the following attributes: the construction, maintenance, operational and land use costs. The transshipment costs are assumed to be included within the operational cost attributes. On the shippers' side, at a first stage, the considered costs are relative to the direct out-of-pocket costs to purchase the itineraries, where their final price is equal to the addition of the prices of each of its constituting services. At a later modelling stage, as it will be shown, this view is further enriched by considering a total logistics costs from the shippers' view, including level-of-service attributes. At all times, the shippers have the possibility of choosing to send their demands over an existing market competition to the intermodal operator, represented in an all-road trucking itinerary that is assigned a fixed price.

In the recent literature on service network design, most models have considered an accurate representation of the services' schedules through multi-period networks and time-discretization techniques (e.g. Andersen et al. (2009); Erera et al. (2013); Boland et al. (2017)). While we acknowledge the practical impact of these operational aspects on the freight consolidation opportunities and resources' utilization, we choose to stick to a tactical scope for consistency purposes as we simultaneously address the typically medium-term pricing decisions. Nevertheless, in our extension of the model as we shall later show, we still attempt to incorporate time-related factors (i.e. delays and transit times) in such a way as to assess the services' quality without adding a considerable load on the computationally expensive bilevel programming framework.

At first glance, our design and pricing approach might seem similar to the presented model in Ypsilantis (2016), however it differs in the fact that, unlike this previous study where every port to hinterland path can go through only one tariff arc providing the problem with a limited, yet privileged structure, a more generalized case is considered where intermodal paths typically incorporate more than one tariff arc/service and services can be shared between multiple paths. Furthermore, the main contribution of our proposed model is the ability to express, in addition to the price attributes, the influence of the freight service quality on the market penetration: a subject echoed by the theories of the shippers' choice behaviour. In order to encompass this wider view, two approaches are introduced and compared against each other. In the first approach, additional constraints are incorporated to set upper bounds on admissible frequency delays, with respect to each shipper's case. In the second approach, a more sophisticated methodology is devised. Namely, at a first stage, based on a binary logit choice model and a Revealed Preference (RP) survey among container shippers in Belgium, a freight mode disutility (or equivalently, logistics costs) function is estimated. At a second stage, the resulting estimation is cast deterministically in the objective of the lower level in the bilevel program. In contrast to the previous recent studies on stochastic network pricing in Gilbert et al. (2014, 2015) where the users are assigned to paths according to a logit model, our proposed approach presents an alternative that still accounts for the probabilistic factor, yet remains computationally simple. Very few previous studies have addressed the expression of the shippers' disutility as a combination of differently weighted attributes, in addition to the out-of-pocket costs, within a bilevel framework (Crevier et al. (2012); Marcotte et al. (2013)). However, the stated references, for instance, do not consider the network design part in terms of design variables. To the best of our knowledge, there was no work that depicted the logistics evaluation concept on a multiple service-line market, within a bilevel design and pricing model, based on the discrete choice theory as we currently propose.

2 A joint design and pricing formulation

In this section, we present a path-based bilevel mathematical program for the joint design and pricing problem. The model is assumed to be static and deterministic, therefore, the market demand is known in advance. In our model, the leader corresponds to the transport operator, the followers to the shippers and the competition to the all-road trucking alternative. The trucks - both used within the intermodal itineraries and the all-road competition - are assumed to be homogenous and always furnished when needed. In the interest of highlighting the particulars of the necessary reformulations and the modelling enhancements, we start by considering only price attributes in the lower-level costs minimization problem.

2.1 Formulation

Let us consider an underlying physical network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, with node set $\mathcal{N}$ and arc set $\mathcal{A}$. A node can be regarded as a supply, demand or terminal node where the transshipment between the different modes takes place. $\mathcal{S}$ denotes a set of freight (in our application context, intermodal) transport services, where each service $s \in \mathcal{S}$ is assigned: a physical arc $a_s \in \mathcal{A}$ in the network; a transport mode m_s (i.e., road, rail or IWWs); maximum allowed units of capacity u_s and a fixed cost f_s of operating service s once in the planning period, typically one week. A set of commodities $\mathcal{K}$ are shipped over the network, where each commodity $k \in \mathcal{K}$ is defined by: an origin and destination pair $(o_k, d_k) \in \mathcal{N} \times \mathcal{N}$; total demand volumes w^k in tonnes; a fixed trucking service tariff R^k to deliver one tonne of commodity k relative to the direct all-road distance separating o_k and d_k and a variable cost v_s^k to transport one tonne of commodity k using service s. A shipper, in our problem, can have a shipping demand, represented in one or more commodities.

It is assumed that the intermodal paths, represented in service-based itineraries, have been generated *a priori* for each commodity. This design decision has been taken to ensure that the intermodal paths are *correctly* constructed, without the need to use supplementary variables or constraints in the model. Correctness is meant in the sense of being geographically feasible and conforming to certain norms of paths' structure, i.e., the long haul is performed by non-road modes and the intermodal distance does not exceed the equivalent all-road one by a fixed margin that is identified through preliminary tests determining the economic viability. The idea is, for each commodity, to scan all possible services emanating from its origin node for candidate paths. Then, starting from each of those services, the algorithm seeks to append a successor one, whose origin node corresponds to the destination node of the currently considered service. This procedure is iteratively repeated until either the maximum allowed number of services along an intermodal path is reached, or the destination of the current commodity coincides with the destination node of the last service along the path in construction. If the latter case is attained, an intermodal path of the commodity is considered to be found. This step results in a set of itineraries $\mathcal{L}^k$ for each commodity k, where each itinerary $l \in \mathcal{L}^k$ is tantamount to a sequence of services ($l \subseteq \mathcal{S}$).

A necessary assumption, that is indeed valid for the European case in general and the Belgian case in specific, is made throughout the model with respect to the availability of a competition's direct trucking alternative for each commodity $k \in \mathcal{K}$. The competition's prices are depicted by the R^k inputs, representing the price of transporting one tonne of commodity k and remain unchanged for the whole planning period. Theoretically speaking, an upper bound on the leader's revenues is given by the total competition's prices of the commodities. It is worth mentioning that, for most practical cases involving complex networks, this upper bound can not be reached for the leader (Labbé and Violin, 2013). An *optimistic* case of bilevel programming is considered; in the case of equivalent lower-level solutions, the leader assumes that the followers choose the most favorable one for him.

Moreover, we define additional parameters δ_s^l for each service $s \in \mathcal{S}$ and itinerary $l \in \mathcal{L}^k$ of commodity $k \in \mathcal{K}$ to link the services to their corresponding itineraries; $\delta_s^l = 1$, if service s is used within itinerary l (0, otherwise). Let us distinguish between the variables of the leader and the followers, represented in the service provider and the target shippers, respectively. At the upper level, for each service $s \in \mathcal{S}$, the leader's decisions are two-fold: a discrete frequency y_s of running s during the planning period and a real-valued associated price T_s of transporting one unit (of any) commodity over it. At the lower level, the real-valued variables h_l^k (respectively, z^k) denote the volumes of commodity $k \in \mathcal{K}$ shipped on the leader's itinerary $l \in \mathcal{L}^k$ (respectively, the competition). In this context, the commodities' demands can be split and the flows' bundling is, thus, made possible. Based on the above notation, the joint design and pricing problem can be expressed as a bilevel MIP formulation with bilinear objectives and linear constraints as follows:

$$\max_{T, y, h, z} \quad \sum_{k \in \mathcal{K}} \sum_{l \in \mathcal{L}^k} \sum_{s \in \mathcal{S}} \delta_s^l T_s h_l^k - \sum_{s \in \mathcal{S}} f_s y_s - \sum_{k \in \mathcal{K}} \sum_{l \in \mathcal{L}^k} \sum_{s \in \mathcal{S}} \delta_s^l v_s^k h_l^k \tag{1a}$$

$$\text{s.t.} \quad \sum_{k \in \mathcal{K}} \sum_{l \in \mathcal{L}^k} \delta_s^l h_l^k \leq u_s y_s \quad \forall s \in \mathcal{S}, \tag{1b}$$

$$y_s \in \mathbb{Z}^* \quad \forall s \in \mathcal{S}, \tag{1c}$$

$$T_s \geq 0 \quad \forall s \in \mathcal{S}, \tag{1d}$$

Where (h, z) solves:

$$\min_{h,\, z} \quad \sum_{k \in \mathcal{K}} \left(\sum_{l \in \mathcal{L}^k} \sum_{s \in \mathcal{S}} \delta_s^l T_s h_l^k + R^k z^k \right) \tag{2a}$$

$$\text{s.t.} \quad \sum_{l \in \mathcal{L}^k} h_l^k + z^k = w^k \quad \forall k \in \mathcal{K}, \tag{2b}$$

$$h_l^k \geq 0 \qquad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{2c}$$

$$z^k \geq 0 \qquad \forall k \in \mathcal{K} \tag{2d}$$

The upper-level objective (1) serves to maximize the leader's net profit, expressed as the difference between the collected revenues from the services' prices T_s and the sum of fixed costs to run the services and the variable costs to transport the assigned commodities. The latter component is assumed to comprise the relevant operational costs for the intermodal operators, including the transshipment costs at the terminals. As intermodal transport is essentially characterized by standardized loading units, such as containers, swap-bodies or semi-trailers, it is valid to suppose a fixed unit handling cost for the transshipment operations. Indeed, a limitation in this considered objective is the absence of cost discounts that are commonly associated with the flow bundling opportunities. The reason is that it would change the functional form of the upper-level problem, potentially requiring linearisation steps and adding considerable computational complexity.

The lower-level objective (2), on the other hand, is to minimize the followers' disutility, currently represented by the out-of-pocket costs of the selected itineraries. Bilinear terms are encountered in both objectives. Constraints $(1b)$ ensure that the sum of the commodities' volumes sent over a certain service does not exceed this service's capacity, according to its selected frequency. Constraints $(2b)$ express the followers' demand satisfaction requirement. Finally, $(1c)$ - $(1d)$ and $(2c)$ - $(2d)$ define constraints on the decision variables of both levels. The nonnegativity constraints of the services' prices $(1d)$ are necessary to exclude the consideration of internal subsidies: assigning a negative price to a service with the hope of reaching a higher objective value. This is theoretically possible in network pricing problems as previously shown by Labbé et al. (1998). However, in addition to this situation being unlikely to happen in a real case, our wider scope of jointly considering design and pricing suggests eliminating this option in order to be able to correctly assess the obtained results. Furthermore, in our considered application scope of pricing intermodal freight transport services, subsidies are commonly provided from external or public budgets.

It is worth commenting on the position of constraints $(1b)$ within the formulation. Such constraints involving variables from both the upper and lower level, known as joint constraints, are not binding to the followers' decisions when they appear in the leader's problem and render the formulation more restricted (Mersha and Dempe (2006)). Generally speaking, the movement of such constraints between the levels can not be performed without altering both the feasible and optimal set of solutions of the bilevel program. However, for the special class of joint design and pricing problems to which our model belongs, Brotcorne et al. (2008) showed that it is possible for joint upper-level constraints to be enforced on the followers' choices through a proper tariff schedule, without negatively affecting the leader's revenues. We do not attempt to carry over the same argument to our model, since according to our problem's interpretation, this global services' design scope essentially belongs to the leader's (transport operator's) view. The followers (shippers) are not typically provided with this information and it does not contribute to their decision.

2.2 Reformulations and enhancements

Following previous authors' methodologies (Labbé et al. (1998); Brotcorne et al. (2000, 2001)), we show how to reformulate the obtained bilevel model as a single-level MIP in order to attempt to solve it. According to our original assumption about the trucking competition's ability to accommodate all demands, a shipper will decide for the leader's itineraries as long as their cost is found to be below or equal to that of the competition's, as an optimistic case of bilevel programs is assumed. Furthermore, a shipper's demand can be split over multiple itineraries, or lost to the competition, given the services' capacity limitations.

The traditional idea of the reformulation is to substitute the lower-level mathematical program by its Karush–Kuhn–Tucker (KKT) conditions as sufficient and necessary optimality conditions. Let $(\lambda_k, \forall k \in \mathcal{K}$ denote the dual variables associated with constraints $(2b)$; note that they are not restricted in sign as they are associated with equality constraints. The following single-level bilinear optimization problem is obtained::

$$\max_{T, y, h, z, \lambda} \quad \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k}\sum_{s\in\mathcal{S}} \delta_s^l T_s h_l^k - \sum_{s\in\mathcal{S}} f_s y_s - \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k}\sum_{s\in\mathcal{S}} \delta_s^l v_s^k h_l^k \tag{3a}$$

$$\text{s.t.} \quad \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k} \delta_s^l h_l^k \leq u_s y_s \qquad \forall s \in \mathcal{S}, \tag{3b}$$

$$\sum_{l\in\mathcal{L}^k} h_l^k + z^k = w^k \qquad \forall k \in \mathcal{K}, \tag{3c}$$

$$\lambda_k \leq \sum_{s\in\mathcal{S}} \delta_s^l T_s \qquad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{3d}$$

$$\lambda_k \leq R^k \qquad \forall k \in \mathcal{K}, \tag{3e}$$

$$\left(\sum_{s\in\mathcal{S}} \delta_s^l T_s - \lambda_k\right) h_l^k = 0 \qquad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{3f}$$

$$\left(R^k - \lambda_k\right) z^k = 0 \qquad \forall k \in \mathcal{K}, \tag{3g}$$

$$y_s \in \mathbb{Z}^* \qquad \forall s \in \mathcal{S}, \tag{3h}$$

$$T_s \geq 0 \qquad \forall s \in \mathcal{S}, \tag{3i}$$

$$h_l^k \geq 0 \qquad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{3j}$$

$$z^k \geq 0 \qquad \forall k \in \mathcal{K} \tag{3k}$$

The lower-level optimality is guaranteed by the primal feasibility (constraints $(3c)$), dual feasibility (constraints $(3d)$ - $(3e)$) and the complementarity slackness (constraints $(3f)$ - $(3g)$). Note that no complementarity is required for constraints $(2b)$ as equality is originally ensured. The resulting formulation is still, however, non-linear, as it comprises bilinear terms in the objective (3) as well as the complementarity constraints $(3f)$ - $(3g)$. In what follows, we clarify how to perform a linearisation step for each of them.

2.2.1 Linearising $T_s h_l^k$

According to the strong duality theorem applied to the lower-level mathematical program, the primal and dual objectives are equal at optimality. Consequently, the first term of the objective function of problem (3) can be rewritten in terms of linear ones as follows:

$$\sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k}\sum_{s\in\mathcal{S}}\delta_s^l T_s h_l^k = \sum_{k\in\mathcal{K}} w^k\lambda_k - \sum_{k\in\mathcal{K}} R^k z^k \tag{4}$$

2.2.2 Linearising the complementarity constraints

In order to linearise the complementarity constraints of the lower-level reformulation, we adopt a similar strategy to that applied by Crevier et al. (2012). Namely, we introduce two binary variable sets: $x_{k,l}^1$ and $x_{k,l}^2$, $\forall k\in\mathcal{K}, \forall l\in\mathcal{L}^k$ to make sure, according to the complementarity slackness' definition, that at least one of each constraint's factors is equal to zero. The feasibility of the loose constraints is ensured through the usage of suitable big M parameters. Constraints $(3f)$ are, thus, linearised as follows:

$$\begin{aligned}
\sum_{s\in\mathcal{S}}\delta_s^l T_s - \lambda_k \le M_{k,l}^1 x_{k,l}^1 \quad & \forall k\in\mathcal{K}, \forall l\in\mathcal{L}^k,\\
h_l^k \le M_{k,l}^2 x_{k,l}^2 \quad & \forall k\in\mathcal{K}, \forall l\in\mathcal{L}^k,\\
x_{k,l}^1 + x_{k,l}^2 \le 1 \quad & \forall k\in\mathcal{K}, \forall l\in\mathcal{L}^k,\\
x_{k,l}^1, x_{k,l}^2 \in \{0,1\} \quad & \forall k\in\mathcal{K}, \forall l\in\mathcal{L}^k
\end{aligned} \tag{5}$$

Similarly, we introduce two binary variable sets: x_k^1 and x_k^2, $\forall k\in\mathcal{K}$ and constraints $(3g)$ are thus substituted by the following:

$$\begin{aligned}
R^k - \lambda_k \le M_k^1 x_k^1 \quad & \forall k\in\mathcal{K},\\
z^k \le M_k^2 x_k^2 \quad & \forall k\in\mathcal{K},\\
x_k^1 + x_k^2 \le 1 \quad & \forall k\in\mathcal{K},\\
x_k^1, x_k^2 \in \{0,1\} \quad & \forall k\in\mathcal{K}
\end{aligned} \tag{6}$$

Accordingly, we obtain a final MIP reformulation for the joint design and pricing problem considering only price attributes in the followers' decisions:

Joint Design and Pricing (JDP)

$$\max_{T,y,h,z,\lambda} \quad \sum_{k\in\mathcal{K}} w^k\lambda_k - \sum_{k\in\mathcal{K}} R^k z^k - \sum_{s\in\mathcal{S}} f_s y_s - \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k}\sum_{s\in\mathcal{S}}\delta_s^l v_s^k h_l^k \tag{7a}$$

s.t.

$$y_s \in \mathbb{Z}^* \quad \forall s\in\mathcal{S}, \tag{7b}$$

$$T_s \ge 0 \quad \forall s\in\mathcal{S}, \tag{7c}$$

$$h_l^k \ge 0 \quad \forall k\in\mathcal{K}, \forall l\in\mathcal{L}^k, \tag{7d}$$

$$z^k \geq 0 \quad \forall k \in \mathcal{K}, \tag{7e}$$

$$\text{Upper-level feasibility: constraints (3}b\text{)}, \tag{7f}$$

$$\text{Lower-level primal feasibility: constraints (3}c\text{)}, \tag{7g}$$

$$\text{Lower-level dual feasibility: constraints (3}d\text{) - (3}e\text{)}, \tag{7h}$$

$$\text{Lower-level linearised complementarity: constraints (5) - (6)} \tag{7i}$$

2.3 Tight values for the big M constants

Designing such disjunctive constraints, as in (5) - (6), calls for the need to use the so-called big M constants. They typically serve to bound the left-hand side, in the case where the corresponding constraints are *loose*. It is generally important to set these big M parameters to the smallest possible values that still yield a valid formulation, in order to make the problem's linear relaxation as tight as possible, and hence potentially improving the performance of the solution methods as we will later show.

2.3.1 Parameters $M^2_{k,l}$ and M^2_k

It is straightforward to infer that the maximum value that bounds the flow variables h^k_l and z^k appearing in constraints (5) and (6) respectively is indeed the corresponding commodity's demand: w^k. And thus:

$$M^2_{k,l} = w^k \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k \quad \text{and} \quad M^2_k = w^k \quad \forall k \in \mathcal{K} \tag{8}$$

2.3.2 Parameters M^1_k

In order to find a proper bound, we are interested to draw conclusions about the dual variables λ_k appearing in the linearised complementarity constraints (6). The dual lower-level mathematical program is a maximization problem, subject to greater-than-or-equal constraints:

$$\max_{\lambda} \quad \sum_{k \in \mathcal{K}} w^k \lambda_k \tag{9a}$$

$$\text{s.t.} \quad \lambda_k \leq \sum_{s \in \mathcal{S}} \delta^l_s T_s \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{9b}$$

$$\lambda_k \leq R^k \quad \forall k \in \mathcal{K} \tag{9c}$$

Note that the dual variables λ_k are not restricted with a sign, as they are originally associated with equality constraints (2b). Provided that $T_s \geq 0$ and, by hypothesis, we consider non-negative competition's prices R^k, the right-hand side of the constraints is also non-negative. We may consequently deduce the non-negativity of the optimal dual solution $\lambda^*_k \geq 0$ for each commodity $k \in \mathcal{K}$. Therefore, R^k bounds the difference $R^k - \lambda_k$ and can be assigned to the corresponding big M parameters.

2.3.3 Parameters $M^1_{k,l}$

Looking at the problem's network set-up, we observe that, unlike the previous reasoning, the competition's prices R^k for commodity $k \in \mathcal{K}$ do not necessarily bound the leader's decisions $\sum_{s\in\mathcal{S}} \delta^l_s T_s$ for a certain itinerary $l \in \mathcal{L}^k$. There could exist some cases, where it becomes in the leader's economic interest to raise the additive prices of the services constituting an intermodal itinerary above that of the competition's all-road alternative. This could precisely occur if and when a common service is being shared by more than one itinerary, each belonging to commodities with different competition's prices. Let $\bar{\delta}^k_s$ be a parameter that takes the value 1 if commodity $k \in \mathcal{K}$ contains service $s \in \mathcal{S}$ within one of its intermodal itineraries and 0 otherwise. Considering all commodities that have any itinerary comprising s, let c_s denote the maximum of their competition's prices. Therefore, the leader's price T_s can be assumed to be bound by this value c_s. This can be mathematically expressed as follows:

$$c_s = \max\left[\bar{\delta}^k_s R^k : k \in \mathcal{K}\right], \quad \forall s \in \mathcal{S} \tag{10}$$

Accordingly, a valid bound to the difference $\sum_{s\in\mathcal{S}} \delta^l_s T_s - \lambda_k$ in constraints (5) can be provided by $\sum_{s\in\mathcal{S}} \delta^l_s c_s$. To this end, a freight mode is solely favoured based on the transport rate its carrier charges the shipper and flows could only be lost to the competition due to capacity limitation.

3 Modelling level-of-service attributes

In reality, several interrelated factors, in addition to the out-of-pocket costs, contribute to a logistics service assessment from the point of view of the target shippers (e.g., inventory holding costs, transit time, service reliability, loss and damage, etc.). In this section, we attempt to extend the developed model in section 2 in such a way as to account for this wider level-of-service perspective. We shall approach this goal in two different ways. First, we model service frequency delays and impose maximum allowed upper bounds through additional constraints, obtaining a model referred to as Joint Design and Pricing - Frequency Delays (JDP-FD) . Second, we incorporate a statistically estimated logistics costs function (equivalently, a disutility) in the shippers' freight mode choice at the lower level of the mathematical program, obtaining another model referred to as Joint Design and Pricing - Logistics Costs (JDP-LC). The JDP model is thus an intermediate step leading towards the next two implemented models and its mathematical properties could be carried over.

3.1 Frequency delay constraints

There is often a debate about the significance of the service frequency, as an attribute indicating the level of the service. In particular, it is considered as a factor that is more influential than the speed. Although a slow mode is generally undesirable inducing a high disutility, when shipments are sent on relatively regular intervals, the length of the transit period tends to receive less importance (Baumol and Vinod (1970)). Despite the role that the tactical decisions play in the eventual operational performance and the resulting services' level, the time aspect has been rarely incorporated in tactical network design models. This also suggests a risk of overlooking the fact that the shippers' freight mode choice, traditionally occurring at a medium-term planning horizon, depends on, among others, their evaluation of time-related service quality.

3.1.1 Background

Very few contributions can be noted in the literature attempting to model frequency-related delays at a tactical level, and their relation, in some cases, to shippers' specific characteristics. In the framework of a planning model for railroad freight transport, Crainic et al. (1984) classify delivery delays in three categories: connection delay, line delay and classification delay. In the authors' interpretation, the connection, or frequency, delay denotes the time cars have to wait before a train becomes available, and modelled to be inversely proportional to the services' frequencies. As a measure of the quality of service, such delay-related costs are incurred, within the objective function, each time a change of service occurs. As observed by Ypsilantis (2016), the structure of the model creates high dependence of the containers' routing on the penalty delay compared to the network operational costs, which can certainly reflect reality, however, it can equally fall into inaccuracy specially in the general case of the approximation difficulty of unit delay costs. Li and Tayur (2005) consider a less debatable formulation for an intermodal application. According to each customer's class, constraints are imposed to ensure that the total transit time does not exceed a previously defined upper bound. In addition to the line delay, as the previous model, the total transit delay also comprises a frequency delay; classification delays are not applicable in intermodal transport. Since actual delays depend on the arrival pattern of the trailers and trains occurring at a later operational level, frequency delays in this medium-term problem are regarded as a random variable having the route frequency as a parameter in its distribution: an eventual decreasing function of the frequency.

In contrast to the above, the effect of the service level on the market penetration with respect to the competition is captured by Ypsilantis (2016) within a joint design and pricing model for intermodal port-hinterland network services. A multicommodity bilevel formulation with differentiated characteristics among the commodities is developed, where constraints are introduced guaranteeing that the expected service time for each commodity does not exceed its defined limit. In their depiction of the considered service time, a transport time, a custom delay, as well as a frequency delay are included. For the latter, an expression similar to the one in Crainic et al. (1984) is considered.

3.1.2 Modified formulation

In our model, we similarly adopt a constraints-based approach to set a minimum standard for the level-of-service, according to each shipping demand case. Assuming that each commodity's maximum allowed delay is known a priori to the leader (or the intermodal carrier), only those intermodal itineraries whose composing services have an operating frequency that meets a minimum standard will be open for selection to the corresponding shipper. A standard, in this context, is meant in the sense of a minimum ratio of the planning period's length to the shipper's maximum delay; thus, the notion of delay can be thought of as the maximum *latency* a shipper can tolerate in order for his demand to arrive on a later service. A simplification is assumed in this regard, by assuming that the maximum delay is uniformly divided over the services constituting the itineraries. An exact depiction of the delay related to the multiple transshipments would imply the design of quadratic constraints and a considerable computational complexity.

Note that for the sake of the model's feasibility, the trucking alternative is always assumed to meet this service frequency requirement. More precisely, let lh be the length of the planning period (typically in days), t^k_{max} the maximum delivery delay allowed by commodity $k \in \mathcal{K}$ (also in days) and $\mathcal{S}^k_l \subseteq \mathcal{S}$ the set of services in itinerary $l \in L^k$. At the upper level, we introduce the binary flow variables $\bar{h}^k_l$ for each itinerary $l \in \mathcal{L}^k$ of commodity $k \in \mathcal{K}$; $\bar{h}^k_l$ takes the value 1 if itinerary l is open for commodity k, and 0 otherwise. The following constraints are added at the upper level:

$$\frac{lh}{t^k_{max}}\bar{h}^k_l \leq y_s \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \forall s \in \mathcal{S}^k_l$$
$$h^k_l \leq w_k \bar{h}^k_l \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k \tag{11}$$

Where the first set of constraints ensure that the variables $\bar{h}^k_l$ are assigned the value 1 only when the itinerary l conforms to the requirements of commodity k, and 0 otherwise. The second set of constraints make sure that when variables $\bar{h}^k_l$ are zero, no flows will be sent over the corresponding itinerary, relating between the binary and the real-valued flow variables. The rest of the formulation in (7) is carried on without any necessary alteration, yielding a new version of the model: JDP-FD.

3.2 Estimated logistics costs

The general behavioural assumption is that shippers seek to minimize their total logistics costs, and thus increase their respective utility. Several individual items interact in complex ways in order to determine the total logistics costs involving commodities', shippers' and shipments' characteristics, in relation to freight charges and the inventory carrying costs. An attempt to minimize a single cost element may result in an increase in the total costs (Ben-Akiva et al. (2013)). Therefore, a choice of a freight mode and a representation of its respective utility must involve a tradeoff among the cost advantages and the nonprice attributes.

The inventory theory is a pivotal reference to the interpretation of the transport mode choice made by shippers. Baumol and Vinod (1970) define four essential components of the total logistics costs expression: (i) direct shipping costs, (ii) in-transit carrying costs, (iii) ordering costs and (iv) recipient's inventory carrying costs. Additional attributes can equally be considered, such as: the loss and damage, reliability and the unavailability of equipment costs, as later applied by Vieira (1992). It was underlined that the concept of annual costs is preferably adopted, as opposed to a by-shipment analysis, to account for the fact of the increasing number of long-term contracts between the shippers and carriers.

Nevertheless, an application of a normative approach provided by similar cost models repetitively fails to coincide with the shippers' actual choices. This is chiefly due to two reasons: the non-uniformity of the service perception among the shippers and the lack of certain significant information for the cost calculation (e.g., the discount rate and the cost per order). The proposed solution, as shown by Vieira (1992) and Ben-Akiva et al. (2013), is to combine discrete choice methods with the minimization of total logistics costs, in the same way that utility maximization is modelled for individuals' choice behaviour in passenger traffic. The shippers' modal selection can be interpreted by a random utility model, where the choice model estimation is in fact an estimation of the missing cost variables information, together with the importance of the different cost components. We show in what follows a similarly adopted methodology to estimate a logistics costs function relative to a shippers' market of interest, having a choice between intermodal and trucking transport alternatives.

3.2.1 Statistical framework

Random utility models generally state that decision makers (shippers, in our case) choose the alternative that maximizes their respective utility. Provided that human behaviour is inherently probabilistic and outsider observers are not capable of measuring the decision makers' utility functions in an exact manner, the utilities are thus treated by the analysts as random variables. What can be observed instead are the choices which depend on those utilities. Therefore, the event of choosing an alternative is considered stochastic with a choice probability depending on the distributional assumption of a certain disturbance term in the utility function (Ben-Akiva and Lerman (1985)). In the context of freight mode choice, the utility of a certain mode i for shipper n can be expressed in the following way (Ben-Akiva et al. (2013)):

$$U_{in} = \mu(logistics\ costs_{in}) + \varepsilon_{in} = \beta X_{in} + \varepsilon_{in} \tag{12}$$

In which μ denotes a negative scale parameter and ε_{in} an unobservable or random component assumed to be independently and identically distributed (i.i.d.). Assuming X_{in} to be the explanatory variables of the model representing the relation between the characteristics of shipper n and the attributes of mode i, the observable part of the function can be further elaborated as the linear combination βX_{in}. Therefore, considering a binary choice case between two alternatives, i and j denoting the intermodal and the all-road choices, the probability that shipper n chooses mode i is given by:

$$P_n(i) = Pr(U_{in} \geq U_{jn}) = Pr(\beta X_{in} - \beta X_{jn} \geq \varepsilon_{jn} - \varepsilon_{in}) \tag{13}$$

Under the assumption that the random components' difference is logistically distributed, the above choice probability can be expressed as follows:

$$\begin{aligned} P_n(i) &= \frac{1}{1 + e^{-(\beta X_{in} - \beta X_{jn})}} \\ &= \frac{e^{\beta X_{in}}}{e^{\beta X_{in}} + e^{\beta X_{jn}}} \end{aligned} \tag{14}$$

In order to find proper estimates of the β coefficients, we choose to apply the conceptually straight-forward approach of *Maximum likelihood estimation*. The method is based on the fact that the observations are drawn by random from the entire population, therefore the likelihood of the whole sample is the product of the likelihoods of the individual observations. The logarithm of the likelihood function is thus analysed as follows (Ben-Akiva and Lerman (1985)):

$$L(\beta) = \sum_{n=1}^{N} [y_{in} \log P_n(i) + y_{jn} \log P_n(j)] \tag{15}$$

Where N denotes the total number of observations, y_{in} and y_{jn} commonly refer to binary variables indicating whether, or not, the corresponding alternative is chosen. Since we can only have access to average modal shares by the shippers, y_{in} and y_{jn} are replaced by the respective fraction of shippers' flows on each freight mode. Consequently, we shall seek estimates of β that maximize the $L(\beta)$ function.

3.2.2 The database

The data collection was based on individual phone interviews, e-mails and internet surveying questionnaires among shipping companies in Belgium. It was ensured that it is generally feasible for the respondents to use trucking or intermodal transport either for long haul deliveries or to reach the ports to accomplish a journey of maritime transport. The shippers were approached in the context of an RP survey, in which they were asked to share their effectuated choices in relation to actual situations. More precisely, client firms of container transport were interviewed about time-average statistics for some of their specific origin-destination (O-D) connections, in order to reflect the effect of the network characteristics uniquely. Additionally, shipper-specific information are elicited with respect to the firms' business behaviour, corridors' and shipped products' requirements, as well as the mode alternatives' attributes. A total of 101 answers were returned from shipping firms whose annual tonnage ranges from 2000 to 10000 tonnes. Table 1 summarizes the modal share results. Moreover, the following figures are deduced from the obtained data and further testify the currently challenged position of intermodal transport in the market:

- Average freight rate increase of intermodal with respect to all-road transport: 28.2%.
- Average transit time increase of intermodal with respect to all-road transport: 98-185.7%.
- Average number of days equipment remain unavailable in all-road transport (n_r): 3 days.
- Average number of days equipment remain unavailable in intermodal transport (n_i): 6 days.

All-road share	Number of observations
<20%	10
20-60%	3
60-90%	6
90-100%	82
Total	101

Table 1: All-road demands' share with respect to intermodal transport

Out of the entire 101 sample observations, 60 were further kept on as *consistent* and *complete* for the rest of the estimation process.

3.2.3 Choice model estimation

We consider a mathematical expression of the total logistics costs - alternatively, the explanatory variables of the random utility model - based on the one provided by Vieira (1992). In his model, Vieira, 1992 assumes that shippers, or the firms they represent, seek to purchase the transport service that *provide the desired movement of goods with minimum annual logistics costs.* These costs include all the expenses related to storing and transporting the goods. It was underlined that annual costs are preferably adopted, as opposed to a by-shipment analysis, to account for the fact of the increasing number of long-term contracts between the shippers and carriers: six months to one year. In addition to the traditional logistics costs components (Baumol and Vinod, 1970), more terms are incorporated so as to reflect the shippers' perception of the service quality. In our adaptation of this choice model, a deterministic case regarding the probability of reaching a stock-out situation at the destination is considered, in which the transit times and final consumer's demands are fixed. We carry over three main cost components: namely, the transportation charges representing the direct service prices/rates, the capital carrying costs as well as the handling and administrative costs related to receiving and shipping an order. The capital carrying costs represent the cost of capital tied up at the following stages:

- In-transit: from the time an order is shipped until it is delivered.
- In inventory: at the destination assuming constant shipment rates per day, i.e., the average inventory is assumed to be one half of the shipment size.
- Due to the unavailability or late arrival of equipment: assuming an average number of days the transport equipment remain unavailable.

The estimation results are obtained by the freeware Biogeme offered by Bierlaire, 2003, developed for the purposes of maximum likelihood estimation of parametric models. For freight mode i, let T_i denote its respective *tariff* as the rate per tonne, d_i the transit time, n_i the average period necessary equipment remained unavailable and q_i the shipment size respectively. We additionally refer to Q as the annual tonnage shipped by the firm. We show in Table 2 the coefficients' results associated with the full list of cost attributes, together with the finally selected terms based on their statistical significance at the 95$^{\text{th}}$ percentile, as indicated by the values of the t-statistics.

Coefficient	Full logistics costs				Final significant attributes			
	Associated term	Value	std err	t-test	Associated term	Value	std err	t-test
β_0 Transportation charges	$T_i\dfrac{Q}{365}$	-0.00589	0.00262	-2.25	$T_i\dfrac{Q}{365}$	-0.0059	0.00259	-2.28
β_1 Capital carrying costs	$d_i\dfrac{Q}{365}+n_i\dfrac{Q}{365}+\dfrac{q_i}{2}$	-0.00809	0.00419	-1.93	$d_i\dfrac{Q}{365}+n_i\dfrac{Q}{365}$	-0.00801	0.00408	-1.97
β_2 Ordering costs	$\dfrac{Q}{q_i}$	-7.93 e^{-05}	0.00065	-0.12	N/A	N/A	N/A	N/A
Objective at convergence		-27.268				-27.310		
ρ^2		0.284				0.283		
Adjusted ρ^2		0.205				0.23		

Table 2: Estimation results of the logistics costs

In the considered context, β_0 is regarded as a scaling parameter, while β_1 and β_2 are behaviourally interpreted as the discount rate per unit of weight and time and the unit cost per order respectively. All coefficients have the correct signs, however the β_2 coefficient displays a negligible estimate and is, hence, omitted in the final model. Moreover, when the attribute expressing the inventory carrying costs at the destination is removed, the estimation significance of the associated coefficient β_1 is enhanced. Provided that the two models demonstrate equivalent validity results, the final one with fewer parameters will be considered for the remainder of this paper. The estimation results show that the shippers in our surveyed market accord a higher weight to the capital carrying costs, in comparison to the direct transport charges: an impression that was primarily shared since the early stages of the surveys.

Let n_i and n_r evaluate to the average number of days the equipment remain unavailable as elicited by the survey. d_l^k denotes the total transit time for each itinerary $l \in \mathcal{L}^k$ of commodity $k \in \mathcal{K}$, expressed as the sum of the line duration and the transshipment delay at the terminals, whereas d^k simply denotes the line delay of the all-road itinerary of commodity k. Therefore, applying the estimated parametric logistics costs expression as the lower-level objective function of the original joint design and pricing model yields the following bilevel program:

(JDP-LC)

$$\max_{T,y,h,z} \quad \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k}\sum_{s\in\mathcal{S}} \delta_s^l T_s h_l^k - \sum_{s\in\mathcal{S}} f_s y_s - \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k}\sum_{s\in\mathcal{S}} \delta_s^l v_s^k h_l^k \tag{16a}$$

$$\text{s.t.} \quad \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{L}^k} \delta_s^l h_l^k \leq u_s y_s \quad \forall s \in \mathcal{S}, \tag{16b}$$

$$y_s \geq 0 \quad \text{and integer} \quad \forall s \in \mathcal{S}, \tag{16c}$$

$$T_s \geq 0 \quad \forall s \in \mathcal{S}, \tag{16d}$$

Where (h, z) solves:

$$\min_{h,z} \quad \sum_{k\in\mathcal{K}} \left(\sum_{l\in\mathcal{L}^k} \left(\beta_0 \sum_{s\in\mathcal{S}} \left(\delta_s^l T_s\right) + \beta_1 \left(d_l^k + n_i\right)\right) h_l^k + \left(\beta_0 R^k + \beta_1\left(d^k + n_r\right)\right) z^k \right) \tag{17a}$$

$$\text{s.t.} \quad \sum_{l\in\mathcal{L}^k} h_l^k + z^k = w^k \quad \forall k \in \mathcal{K}, \tag{17b}$$

$$h_l^k \geq 0 \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{17c}$$

$$z^k \geq 0 \quad \forall k \in \mathcal{K} \tag{17d}$$

The necessary reformulations and linearisation steps, as applied in model (7), can be similarly invoked on the above bilevel program without the need of any additional assumptions as the modification essentially takes place in the lower-level objective.

4 Computational results

The following computational tests aim at showing the ability to solve the proposed models, as well as comparing the results with those observed in actual transport practices. The three developed versions of the model have been tested on instances of freight demands. Our data represent real-world practices that are in general seldom available at a granularity level that can allow for accurate research. The considered networks resemble those on which the logistics costs estimation procedure was conducted, thus the concluded relative performance of intermodal transport and trucking can be extended to these experiments as well. More precisely, the demand flows data regarded for these experiments were obtained from Carreira et al. (2012) at the second level of the Nomenclature of Territorial Units for Statistics (NUTS 2), based on the accessible Worldnet database for Europe (Newton (2009)). Two transport modes are considered: road and rail, in order to have a basis of comparison with real-world flows, however, the model can be easily generalized to other modes. The generated intermodal itineraries are composed of at most three service legs, subject to feasible extension, with no restriction on the modes' succession. Three main instances are defined based on the geographical information provided by RailNetEurope about the rail freight corridors passing through Belgium, as the market point of interest in our study: namely, the Rhine-Alpine (instance 1), North Sea-Mediterranean (instance 2) and the North Sea-Baltic (instance 3) corridor. The network is assumed to be fully connected in terms of road services; rail services are defined based on the existence of compatible terminals at both the starting and ending points. As described before, for each O-D pair, a direct all-road connection is ensured, whose price is fixed in the model and subject to a sensitivity analysis as we will later show. Finally, the considered transport service costs, as stated in Schroten et al. (2011) and validated by the panel of experts of the project BRAIN-TRAINS, comprise: the construction, maintenance and operational and land use costs. The study further provides a fixed and variable parts division of the costs, with respect to each transport mode. Experiments have been run on an Intel Xeon CPU ES-2620, 2.10GHz workstation with 32.0 GB RAM and 64-bit Windows 10 Pro. The code is implemented in Java using the IBM ILOG CPLEX 12.6 library as a Branch-and-Bound (B&B) solver with default parametrisation.

Different tests highlighting the computational impact of the calculated values of the big M parameters are presented in Appendix A. In Table 3, we invoke the three developed versions of the model on the considered instances and underline how they differ among each other in terms of the CPU times in seconds, the gap representing the difference in percent between the optimal integral solution and the linear relaxation, the resulting market share in percent and the net profit in monetary units. We consider a total size of 64 commodities and 30 nodes for instance 1, 164 commodities and 21 nodes for instance 2 and 74 commodites and 32 nodes for instance 3 respectively. Note that for both instance 1 and 3, we eliminated shipping demands that take place on a distance less than 800 km in order to put forward the effect of large-distance freight demands on the obtained results with respect to intermodal transport. We further consider a realistic figure of the all-road price to be 0.07 Euros per ton-kilometer (EUR/tkm) and all results are obtained within a gap of less than or equal 5% of the optimal solution. Note that optimality could indeed be reached using the same models on smaller instances; e.g., optimal solutions are obtained for instance 3 considering up to 28 nodes and 44 commodities. Similarly, less (or more) than average-valued all-road prices render computational times more affordable for the considered instances in their full sizes. We notice that the computational times are significantly less for instance 2 for the JDP and JDP-FD models, despite its having a larger number of commodities, potentially attributed to the comparably less number of nodes it considers which understandably reduces the itineraries' search space. Note that the average number of generated itineraries per commodity for instance 2 is 13 itineraries, as opposed to 63 and 43 itineraries for instance 1 and 3, respectively. However, this remark does not hold for the JDP-LC model which has apparently created a challenging costs' schedule to resolve, considering the additional logistics costs' attributes and the large number of commodities. The results additionally confirm the reasonable correlation between the market share and the corresponding net profit in most cases; the two attributes are directly proportional, however, the profits tend to show a faster decline with respect to the market shares. In general, the JDP-FD model exhibits the sharpest decrease in the resultant market share with respect to the original JDP model, which is a conceivable behaviour due to the presence of additional requirements on the minimum acceptable service frequencies and the inability, in that case, to maintain the same share of the served market while generating profits. The decrease is slightly less pronounced for instance 2, as services tend to be more affordable over shorter distances. Nevertheless, this version of the model could be regarded as a too normative situation for real life; shippers do not commonly impose similar hard constraints in their choices, but they rather adopt a more global reasoning in the evaluation of their utility, which is more closely depicted in the JDP-LC model. In that sense, the market share is slightly affected for instance 1 and 3, with respect to instance 2, when incorporating the logistics costs at the lower level. This observation is greatly in line with the general impression of intermodal transport becoming more viable over long distances and with the presented opportunities for freight consolidation, while maintaining an acceptable level of the services.

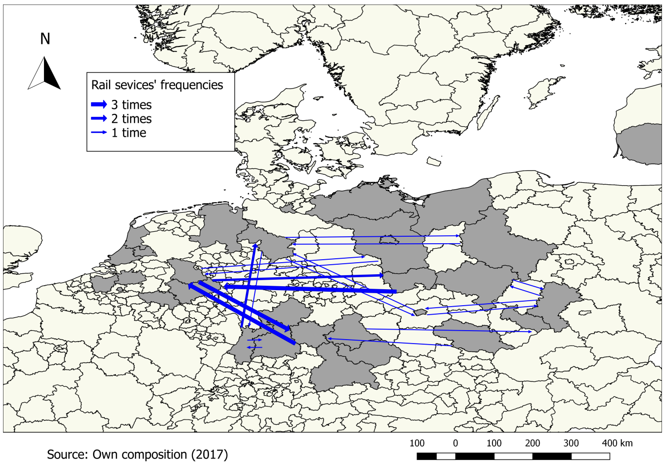
	Instance 1				Instance 2				Instance 3			
	CPU (s)	Gap	Intermodal share	Net profit	CPU (s)	Gap	Intermodal share	Net profit	CPU (s)	Gap	Intermodal share	Net Profit
JDP	4840	5%	97.1%	1218303.9	<550	5%	95.6%	1711723.9	750	3%	94.45%	980974.8
JDP-LC	3755	3%	96.73%	1057445.9	24822	5%	74.89%	837463.6	9218	2%	94.43%	823092.3
JDP-FD	9040	5%	54.15%	574613	1400	3.5%	79.2%	1000816.2	4300	5%	43.4%	225396.8

Table 3: Results of the three models on the considered instances

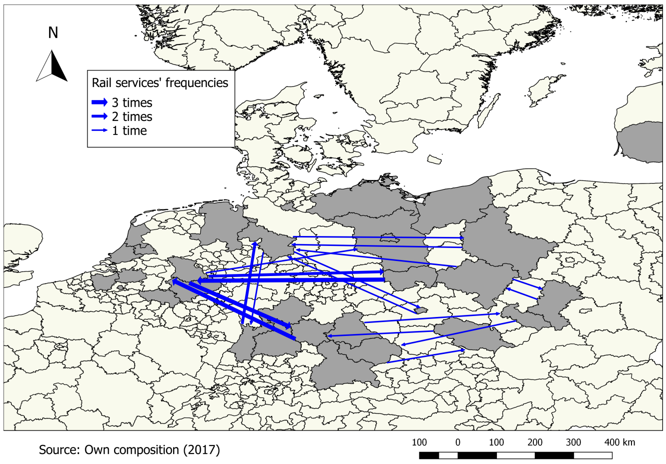
In order to better illustrate the characteristics of the obtained solutions, we hereby show in Figure 1 the output rail services of the three models on instance 3, corresponding to the North Sea-Baltic corridor. This specific instance was chosen for geographical illustration as it runs through the largest number of EU member states among the considered instances. The NUTS 2 points, equivalently the network's nodes, are shaded on the map and the arrows linking between them denote the resulting rail services of each of the invoked models and their frequencies. We start by observing the concentration of the generated rail network around the central region: essentially Germany, Czech and Poland. Although the network does not extend to include all the considered countries as it is the case in the actual corridor, it conforms to a great extent to the existing network layout which similarly reveals a central hub within Germany (European Commission (2017)). In the migration from the basic JDP model to the JDP-LC model, we notice the disappearance of some short-distance services and their replacement by different ones that are arranged in such a way as to form long-distance transport chains carried up by rail (e.g., multiple-leg service lines are created in Southern Czech and Poland). This modification highlights that, in the case of an exerted weight on the service quality, longer rail chains can generate more opportunities for freight consolidation, hence an enhanced, and potentially more affordable, service. The results of the JDP-FD model only keep on the round rail connection Düsseldorf-Dresden, as it is understandably the only affordable and central connection that can be offered at a minimum frequency of 7 times per week, as the maximum allowed latency is generally taken to be the all-road needed duration to run an equivalent distance: 1 day in this case. According to the European Commission (2015), there was a high dominance of road transport at the national level by 69% in the countries along the regarded corridor in 2010, approximately the same period of our considered freight demand data. Our results show a modal split of nearly 46% for road transport. It is also notable that the obtained market shares in general differ from those in the collected database in Table 1. These differences can be attributed to several factors; (i) political aspects and business commitments are not explicitly depicted in our mathematical model, (ii) modal choices are repetitively effectuated based on past experiences which are not entirely playing in the favour of intermodality as a fairly recent transport scheme (note that the majority of the survey's database refers to the dominance of trucking) and (iii) the model portrays a single intermodal operator who is fully and rationally capable of tackling the service pricing and design questions in order to attain the most profitable outcome whereas, in real life, several carriers are operating through the corridor under a potential competition.

Additionally, we plot the relationship between different prices of the all-road transport parameter against the resulting intermodal market share and the profit margin calculated as the ratio in percent of the net profit to the total revenues. Instance 2 and 3 are regarded for this experiment and results are also obtained within an optimality gap of at most 5%. An increasing all-road price obviously results in a bigger opportunity for the intermodal operators to make up for the incurred costs of their offered services, hence, a higher market share and profit margin. We observe that the JDP model incites a beginning of flows' diversion to intermodal transport at an early stage in contrast to the other two models, and similarly continues to dominate for the following average figures of the all-road price parameter. This could be interpreted by the additional burden exerted on intermodal operators to keep up to a certain service quality, as explained before. Another remark that holds for both experiments is that the rate of increase of the profit margin is noticeably slower than that of the market share, since, in covering more market, both the revenues, as well as the costs increase. The small decrease step in the profit margin of instance 3, in the case of the JDP-FD model, can be explained by the additional services that have become affordable at this new all-road price level; notice the relative market share stagnation at the previous levels for the same experiment. The results lastly confirm that our choice of the all-road price parameter (0.07 EUR/tkm) was indeed a reasonable average value.

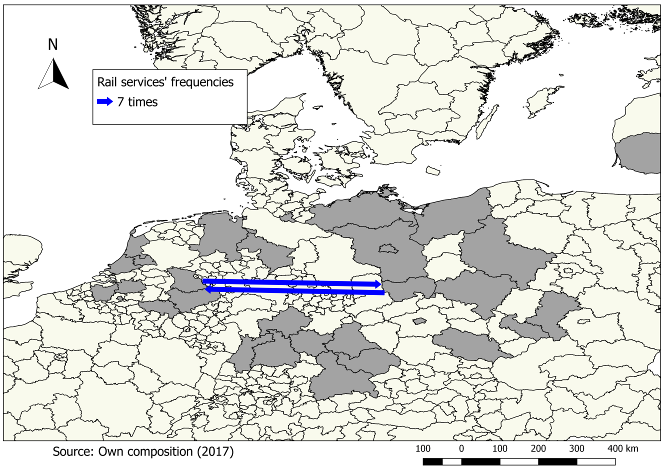
Finally, we look more closely on the managerial insights by performing three sets of experiments related to varying specific operational factors and investigating their potential impact on the future success of intermodal transport. This study is conducted within the view of the BRAIN-TRAINS project. First, we test the effects of subsidising rail transport on the subsequent modal split and train load factor. Second, the train capacity factor is studied with respect to the breakdown of costs and net profit, on one hand, and the flows repartition, on the other. Lastly, in the context of a future scenario analysis, we compare a current reference to a potential best-case scenario with the aim of



(a) Results of the JDP model



(b) Results of the JDP-LC model

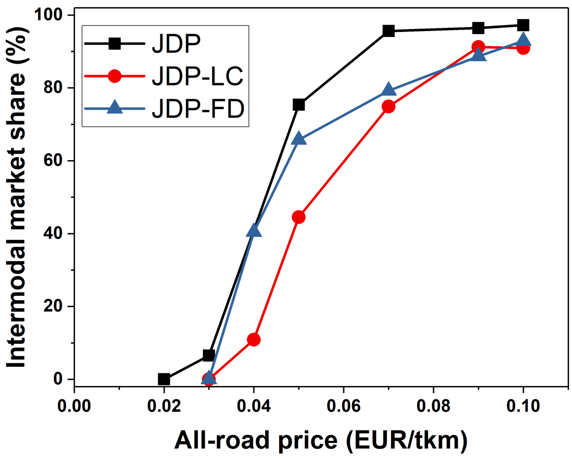


(c) Results of the JDP-FD model

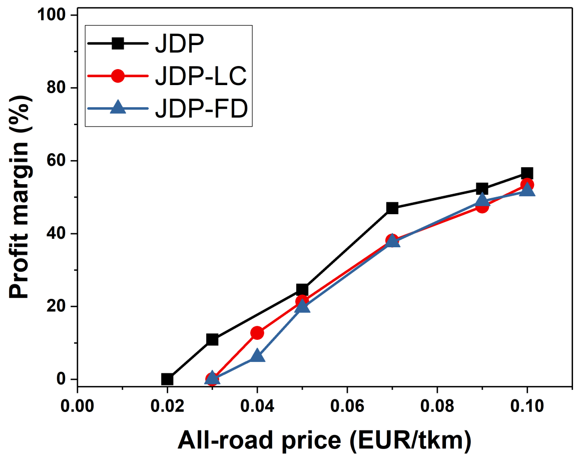
Figure 1: The output rail services of instance 3

providing educated insights on the most influential instruments on intermodality's competitiveness. In what follows, we share the important findings and discuss them with respect to the current and foreseen transport practices and policies, whereas the computational details of the related experiments are outlined in Appendix B.

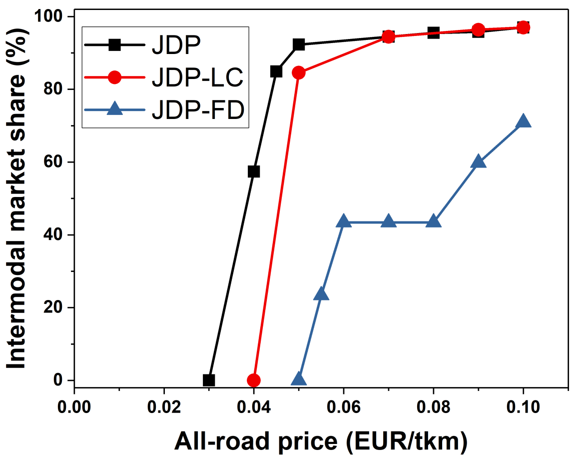
Rail subsidies The general consensus among rail freight services' providers is that subsidies are crucial for the business' survival. Several instruments contribute - with varying levels - to collectively determine the competitive conditions among transport modes, e.g. infrastructure quality, externalities, regulation and land use as well as subsidies. In a technical European report focussing on quantifying transport subsidies (European Environment Agency (2007)), subsidies are defined to encompass the provision of infrastructure, direct transfers, differences in fuel taxation as well as Value Added Tax (VAT) exemptions. The report further shows with quantified values that, in contrast to road, rail transport receives subsidy shares exceeding their share of transport volumes. Although, a decision to promote a certain transport mode should not be solely driven from transport volumes, these figures show the continuing need for rail transport to be supported as it represents a particular case of supporting an environmental cause, in line with the general direction in Europe. This view has already been repeatedly adopted



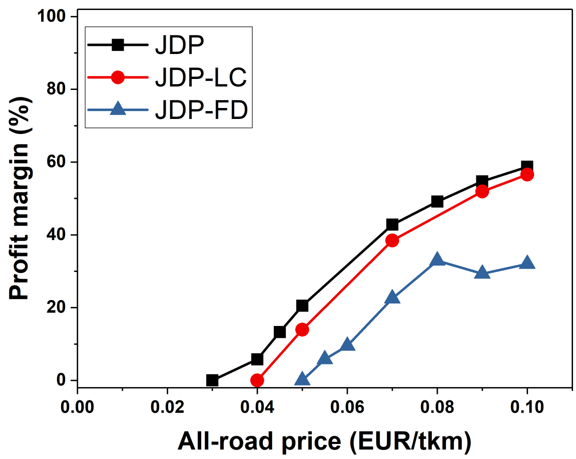
(a) Market share results for instance 2



(b) Profit margin results for instance 2



(c) Market share results for instance 3



(d) Profit margin results for instance 3

Figure 2: Relationship between the all-road price and the resulting market share and profit margin

and resulted in significant outcomes. For instance, in Switzerland, several practices have been applied including road traffic restrictions for lorries and subsidies for companies carrying out rail-road combined transport, resulting in 170% higher modal share of rail freight than the EU average (European court of auditors (2016)). A comparable increase can be observed in Austria which also applied similar regulatory measures. However striking an optimal level of offered subsidies is not a trivial task; in Germany, the Long-Distance Rail Freight Network Funding Act, which made possible since 2013 to provide federal subsidies amounting to 50% to investment in replacement infrastructure by non-federally owned railways, is being currently evaluated in terms of target achievement and potential for optimization, in light of the present and future requirements (Federal ministry of transport and digital infrastructure (2017)).

Our scope in this part is on rail transport subsidies that are paid or granted directly from public funds. Indeed, our experiments confirm that the original breakdown of the costs and net profit of the considered instances - when no subsidies are provided - reveals that the biggest share is obviously attributed to the rail fixed costs (over 50%). Nevertheless, determining an optimal level of rail subsidies is not a trivial task and can potentially differ from one case to another. Our experiments show that the rail subsidies have clearly helped migrate the freight volumes from the all-road to the rail transport, however, the PPH shares remain for the most part unaffected. Furthermore, it is noticeable that the low subsidy levels are met with an opposite all-road share decrease to the favor of rail transport, until a certain threshold after which both experience a stagnation and it becomes pointless to increase subsidies. A potential indicator of this threshold could be the relative comparison between the net profit and the subsidies; when the percentage of the latter starts to exceed that of the former, the consequent impact on the modal split becomes less noticeable. Lastly, with the exception of the high subsidies' levels, the train load factor has been successfully optimized and has remained quite high (97-99%) throughout the different tests.

Rail capacities Currently, the EU is focusing on establishing a standard train length of 740 m (European Commission (2016b)). Nevertheless, due to operational restrictions, this criterion may vary throughout the network (e.g. the maximum train length in Spain and Denmark is 600 m and 835 m, respectively). Despite this situation, future plans to adopt longer trains are already being evaluated as a promising measure to respond to the expected rise in freight volumes (more than 80% by 2050) and in order to avoid further losses in the freight modal split (Community of European railway and infrastructure companies (2016)). It is believed to be an instrument that could improve the operational efficiency of the rail freight system, allowing for a consequent increase in transport capacity. From a railway undertakings' point of view, the volumes of goods that can be transported by a single train can be increased by 35% (1,000 m train) and up to 103% (1,500 m train), in comparison to the current train of 740 m.

Within this view, we put to the test the factor of the train capacity with respect to the cost and net profit of the intermodal service providers, as well as the freight modal split. The first observation is that the net profit of intermodal operators is decreasing with increasing capacities. Similarly, though not steadily, both the fixed and variable rail costs are increasing with increasing capacities, unless a flow repartition takes place and the PPH parts increase. This observation, though valid considering the maintained high train load factor, is not doing enough justice to the perspective of increasing the efficiency of resources' deployment through higher capacities. In principle, not all of the expenses for operating a freight train increase with the length of a train; some can be considered as independent from the length to some extent (e.g. expenses for locomotive and train drivers). Unfortunately, this is not properly depicted in the considered costs' components, as it calls for a precise estimation of the costs' division.

Furthermore, a small increase in the rail capacity (up to 50%) could potentially help slightly increase the intermodal and rail shares. If trains with higher capacities become the norm, a rational reasoning would lead the service providers to optimize their load factor, which has indeed been observed as shown in Appendix B. For small increases in capacities, no considerable load is added on the costs and this results in a slight enhancement in the market coverage rather than refraining to offer the services. Nevertheless, the consequent decrease in net profits should be addressed by proper measures, if the general intention is to help promoting environmental transport modes.

Best-case scenario analysis In this final part, a scenario analysis approach is adopted to identify the impact of different plausible situations on the future development of intermodal rail transport. The aim of a scenario is essentially to offer insights into the future, without attempting to forecast its exact nature (Troch et al. (2017)). In this context, our developed modelling framework is applied to the best-case scenario values of the most important and probable operational parameters, in line with the modal shift goals set by the European Commission (2011).

The consistent observation among the considered instances is that rail costs have the highest impact on enhancing the rail shares. In contrast, road taxes, though initially an instrument to deter flows from all-road transport, it would harm the net profit share of the intermodal operators. This is in part attributed to the costly PPH parts in the intermodal itineraries; the envisaged road taxes are not a sufficient catalyst to shorten the PPH distances. In an overall future best-case scenario, rail-based intermodal transport would indeed have an advantageous position over all-road transport. However, if we look closely on the modal split, without differentiating between all-road and PPH, we would see that the target 30% shift from road by the year 2030 would still not be met in certain cases; only about 10% and 20% shift have been achieved in the best cases.

Conclusion

Driven by an application in intermodal freight transport, a bilevel service network design and pricing modelling approach is put forward. The upper level portrays an intermodal operator that jointly selects the frequency levels of his offered services as well as their associated prices in the quest of profit maximization, whereas, at the lower level, shipping companies decide on the flows of their demands to send over the leader's itineraries, or an always available competition's alternative, represented in an all-road path. In a notable addition to the traditionally considered out-of-pocket costs at the lower level, the model explicitly accounts for the level-of-service attributes in two proposed manners: adding frequency delay constraints in the leader's problem and incorporating an estimated logistics costs function in the objective of the followers' problem. In order to increase the realism of our study, the second approach is devised using the methods of discrete choice analysis in the transport theory.

Equivalent tightened MIP formulations are reached and invoked on real-world instances that correspond to actual freight transport practices in Europe, taking Belgium as a point of interest. All models yield reasonable results that significantly conform to their actual figures within a small optimality gap. However, the computational times suggest a potential room for algorithmic developments to be able to handle larger and more interesting instances. In particular, heuristic algorithms could provide a promising research avenue for this purpose, addressing the main areas of complexity of the problem: the services' design and the lower-level optimality. Brotcorne et al. (2008) provide a relevant contribution along this direction, by extending a primal-dual heuristic algorithm for bilevel programs in the context of a Lagrangian relaxation framework. However, further algorithmic developments are in order to be able to handle the new integral design variables.

The computational tests further show that the broader consideration of the service quality imposes, as expected, a higher cost on the leader and is hence reflected in the resulting market share and net profit. However, this influence is less pronounced on instances over long-distance freight corridors, with the consolidation opportunities coming into play. The quick and sharp decreases in the covered market suggest the normativeness of the JDP-FD approach with respect to the JDP-LC approach, and therefore, the latter is preferred as it adopts a more aggregate view. Moreover, although the application of the JDP-LC model does not result in a significant change in the leader's profit margin, it inflicts a better extended and connected services' layout: a design-related observation that is indeed useful for the transport operators in order to be capable of affording higher service qualities.

In what concerns the managerial insights, we demonstrate the necessity of rail subsidies to overcome its high fixed costs up until a case-dependent threshold, after which the potential to obtain a modal shift undergoes a stagnation phase. A small increase in the rail capacity could slightly enhance its modal share, however a deeper analysis is needed to derive a realistic cost division, and hence correct the possible decrease in intermodal profits with the future longer (and heavier) trains. In a future best-case scenario, even though intermodal transport would receive a higher market share, the desired modal shift goals would still not be attained by 2030: a concern that should be addressed by stronger political measures early on.

Finally, as a research outlook, this work could be further developed by considering a realistic oligopolistic market at the intermodal transport side, representing a competition between several intermodal transport operators. Nevertheless, depicting such an aspect requires a drastic mathematical transformation of the considered framework. In specific, it requires the development of a multi-leader bilevel program, seeking an equilibrium at the upper level: a problem that is significantly computationally expensive. Along the same line, in the presence of the liberalization of the rail industry in Europe, it would be interesting to represent a multi-layer model. It could potentially differentiate between the decisions of the main stakeholders: the infrastructure manager, the service operators and the shippers.

Appendices

A Computational impact of the tight big M parameters

In this part, we seek to demonstrate the advantage of the calculated sharp values of the big M constants using the basic formulation (JDP). In Table 4, the model is invoked, once with arbitrary high values of the parameters (BM) and once with the tight values (TM), on three different problem's sizes of nodes and commodities for each of the considered instances. The results are compared in terms of the CPU times, always in seconds, and the optimality gap. The calculated values bring computational benefits in most cases. Nearly equal gaps are reached in substantially longer computational times using the high parameter values, when compared with the tighter formulation, as it is clearly shown with all the considered instances. Similarly, wider gaps were occasionally reported, for example with instance 3, for the same computational time.

		Instance 1			Instance 2			Instance 3		
		30 nodes, 75 comm.	34 nodes, 113 comm.	38 nodes, 131 comm.	19 nodes, 102 comm.	20 nodes, 126 comm.	21 nodes, 164 comm.	20 nodes, 48 comm.	26 nodes, 98 comm.	32 nodes, 198 comm.
JDP (TM)	Gap	2.8%	3.3%	5%	3%	3.75%	5.02%	3%	<13.5%	13%
	CPU (s)	<1800	<3700	<7500	<1120	<1500	<550	<950	2000	<2800
JDP (BM)	Gap	3%	5.75%	5.12%	3.4%	3%	5.9%	3%	17%	13%
	CPU (s)	>3700	4000	>10000	>3500	>3500	>2050	>1400	2000	>3400

Table 4: Computational effects of the enhanced big M parameters

B Computational tests for managerial insights

To ensure the soundness of the obtained results, we consider for the following experiments a reduced version of the data sets in order to guarantee optimality. Having intermodality as the main scope of these tests, it is relevant to focus our study on long-haul rail connections (i.e. over 300 km): a view that is consistent with the goals indicated by the European Commission (2011) for the desired modal shift of freight flows. We update the data instances 1, 2 and 3 relative to the previously considered freight corridors with respect to this narrowed perspective, yielding instances consisting of 17 nodes and 40 commodities, 19 nodes and 44 commodities and 20 nodes and 58 commodities, respectively. We shall refer to these instances as instance 4, 5 and 6. Furthermore, the JDP-LC model, being the most advanced version, is the one used for this analysis. It is noteworthy to underline that the results highly depend on the considered parameters, which makes this study essentially of a theoretical basis. Nevertheless, in addition to the wide range covered within the parameters' variation, we tend in these experiments to draw high-level insights that are generally applicable, which suggests in turn the practical relevance of the conclusions.

B.1 Rail subsidies

The considered subsidies levels are quantified in terms of monetary units (Euros) per distance and represented as a percentage of the fixed costs. In Figure 3, we express the costs and the net profit in terms of the total revenues' units. A necessary hypothesis to our case study is thus made that the revenues are always greater than or equal to the costs, so that the net profit and the costs would amount to 100%. Our presented model is considered as a relevant framework for these experiments, as it represents a clearly defined costs and net profit breakdown that allows for a proper economic assessment of the impact of introducing rail subsidies on the practices of intermodal operators and the market of shippers. Furthermore, the observed changes in modal split reflect the underlying changes in the service network structure (i.e., introducing more rail connections), which, in turn, could give useful insights on the required capacities. A complete framework would include as well the decision level of the infrastructure managers, as it suggested in the perspectives.

In Figure 4, we further plot for each of the considered instances the modal split in terms of the respective shares of the all-road, PPH and rail transport, where the sum of the last two amounts for the resulting intermodal market share. Looking closely at the road share curve, we see it starts to decrease from the early subsidies' levels, until it undergoes a sharper decrease at a certain threshold that is usually met by an opposite increase in rail share, after which it experiences a stagnation. This threshold has been discussed in Section 4. Moreover, in contrast to instance 4 and 5, the rail share in instance 6 continues to increase until the end; this is closely entwined with the parallel relative decrease in the PPH share. The size of intance 6, being the largest, has potential contributed to this observation, creating a higher possibility for freight consolidation and itineraries' redesigning where longer rail connections could be justified.

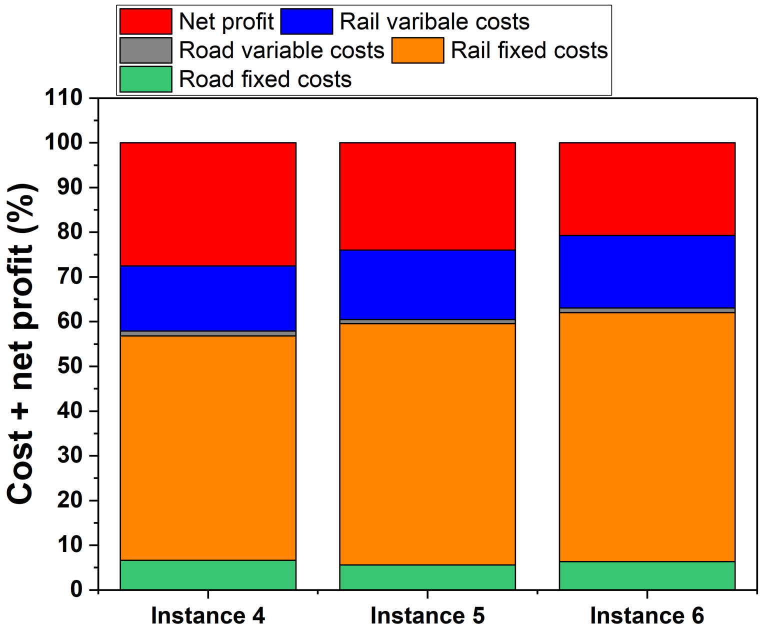


Figure 3: Original costs and profit of intermodal transport

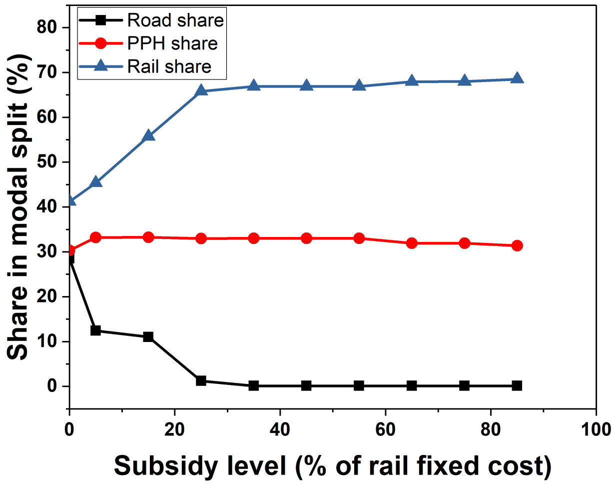
B.2 Rail capacities

As a basic unit of rail service, we consider the Conventional Intermodal Freight Trains (CIFTs), already operating in many national and Trans-European corridors. Typically, each train consists of a maximum of 30 wagons of an approximate length of 20 m (total maximum length of 600 m), each of which has a carrying capacity of 50 tonnes, according to the European Commission (2007) cited by Janic (2008). This represents the capacity unit, according to which we conduct our experiments. In Tables 5, 6 and 7, we show the results related to both decreasing and increasing the train capacity for instance 4, 5 and 6, respectively.

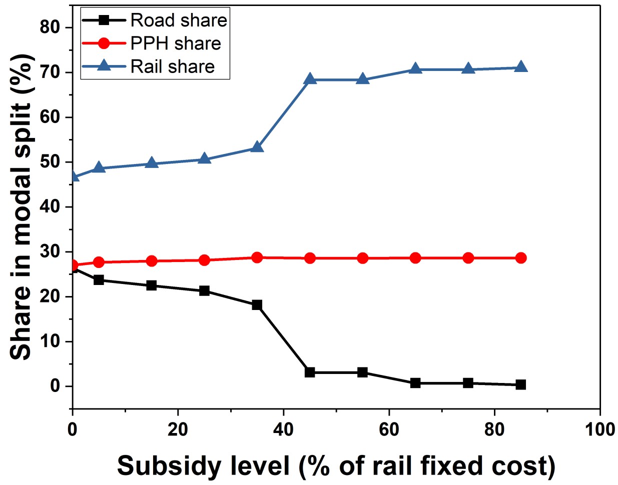
Capacity change	Instance 4					
	Net profit and costs (%)					Objective value (EUR)
	Net profit	Fixed road costs	Fixed rail costs	Variable road costs	Variable rail costs	
-50%	28.42	6.77	49.37	1.11	14.33	499274.80
-25%	28.51	6.78	49.29	1.12	14.30	493515.43
+/-0%	27.54	6.64	50.17	1.09	14.55	488019.30
+25%	25.50	6.23	52.13	1.02	15.13	487431.81
+50%	25.14	6.38	52.26	1.05	15.17	473076.87
+75%	24.63	6.07	52.94	1	15.35	458128.33
+100%	24.51	6.03	53.07	0.99	15.40	458748.26

Table 5: Rail capacity's impact on the revenues (instance 4)

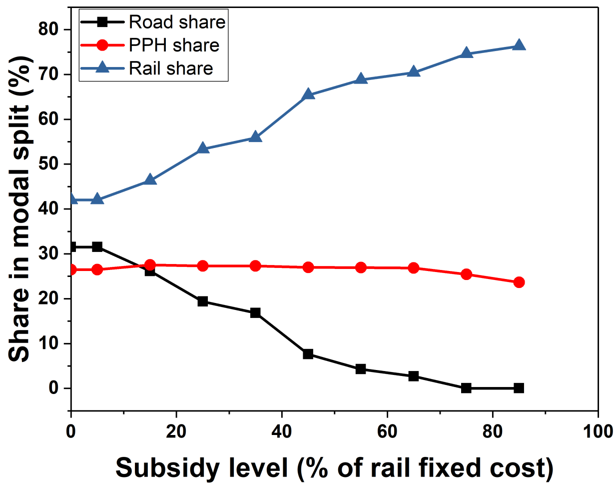
In Figure 5, the modifications in rail capacities are plotted against the respective changes in modal split. Some of the withdrawn remarks do not extend to instance 6, as it represents a larger market with more geographically scattered demands, which makes consolidation a harder task and renders connections with smaller capacities more economically manageable.



(a) Instance 4



(b) Instance 5



(c) Instance 6

Figure 4: Rail subsidies impact on the modal split

B.3 Best-case scenario analysis

The BRAIN-TRAINS project proposed different important parameters to consider when dealing with intermodal and rail transport, in the form of a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis (Troch et al. (2015)). Based on their relevance and plausibility, a selection of parameters have been further made by a panel of experts, using the so-called Delphi method, and quantified according to the considered scenario (best-, worst- and middle-case). A reference is taken to be the current situation. Table 8 shows the results of testing the JDP-LC model according to the best-case scenario values of the operational parameters.

The first row in Table 8 shows the result when all the parameters are tuned to the reference scenario. In the subsequent rows, we refer to the parameter whose value is changed to the best-case scenario values, in order to test the effect and significance of each parameter separately until we arrive, at the last row, where all parameters' values are modified according to the best-case scenario.

Capacity change	Instance 5					
	Net profit and costs (%)					Objective value (EUR)
	Net profit	Fixed road costs	Fixed rail costs	Variable road costs	Variable rail costs	
-50%	20.08	5.63	53.82	0.93	15.55	401480.23
-25%	24.05	5.60	53.90	0.92	15.53	398883.04
+/-0%	23.97	5.58	53.98	0.92	15.55	389444.21
+25%	23.53	5.71	54.27	0.94	15.54	369335.96
+50%	21.69	5.60	55.80	0.92	15.99	352702.49
+75%	23.98	5.81	53.75	0.96	15.51	349596.39
+100%	22.97	5.69	54.88	0.94	15.53	345163.02

Table 6: Rail capacity's impact on the revenues (instance 5)

Capacity change	Instance 6					
	Net profit and costs (%)					Objective value (EUR)
	Net profit	Fixed road costs	Fixed rail costs	Variable road costs	Variable rail costs	
-50%	21.77	6.48	54.79	1.06	15.89	422995.90
-25%	21.43	6.44	55.08	1.06	15.98	412718.83
+/-0%	20.76	6.32	55.73	1.04	16.16	394169.27
+25%	20.86	6.35	55.62	1.05	16.12	380927.28
+50%	20.04	6.27	56.31	1.03	16.34	374121.29
+75%	20.62	6.22	55.98	1.02	16.16	358216.27
+100%	19.34	6.24	56.89	1.03	16.51	345728.88

Table 7: Rail capacity's impact on the revenues (instance 6)

Acknowledgement

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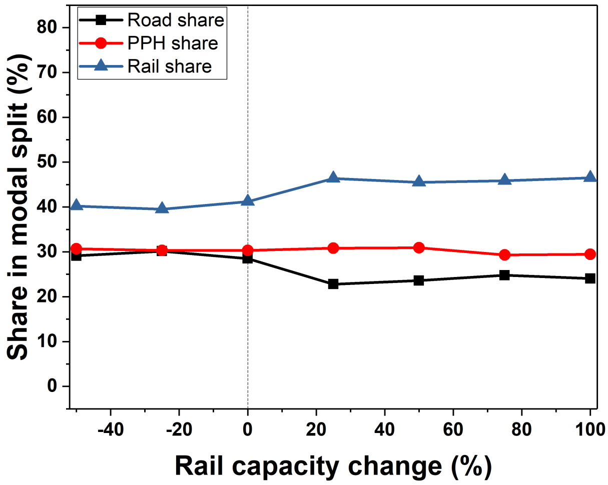
References

Andersen, J., Crainic, T. G., and Christiansen, M. (2009). Service network design with asset management: Formulations and comparative analyses. *Transportation Research Part C: Emerging Technologies*, 17(2):197–207.

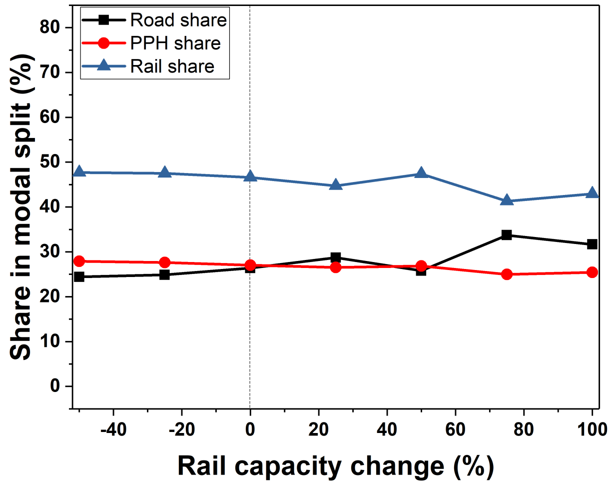
Baumol, W. J. and Vinod, H. D. (1970). An inventory theoretic model of freight transport demand. *Management science*, 16(7):413–421.

Ben-Akiva, M., Meersman, H., and Van de Voorde, E. (2013). *Freight transport modelling*. Emerald Group Publishing Limited.

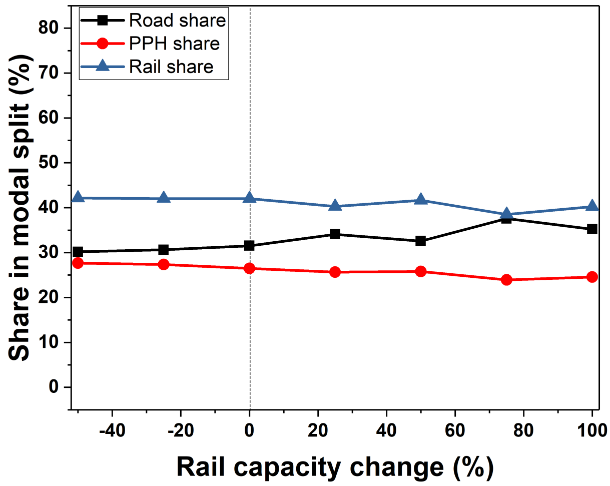
Ben-Akiva, M. E. and Lerman, S. R. (1985). *Discrete choice analysis: theory and application to travel demand*, volume 9. MIT press.



(a) Instance 4



(b) Instance 5



(c) Instance 6

Figure 5: Rail capacity impact on the modal split

Bierlaire, M. (2003). Biogeme: A free package for the estimation of discrete choice models. In *Proceedings of the 3rd Swiss Transportation Research Conference, Ascona, Switzerland.*

Boland, N., Hewitt, M., Marshall, L., and Savelsbergh, M. (2017). The continuous-time service network design problem. *Operations Research*, 65(5):1303–1321.

Bontekoning, Y. M., Macharis, C., and Trip, J. J. (2004). Is a new applied transportation research field emerging?—-a review of intermodal rail–truck freight transport literature. *Transportation Research Part A: Policy and Practice*, 38(1):1–34.

Bracken, J. and McGill, J. T. (1973). Mathematical programs with optimization problems in the constraints. *Operations Research*, 21(1):37–44.

BRAIN-TRAINS (2014). Http://www.brain-trains.be/.

Parameter	Instance 4				Instance 5				Instance 6			
	Modal split (%)			Net profit	Modal split (%)			Net profit	Modal split (%)			Net profit
	Road	PPH	Rail		Road	PPH	Rail		Road	PPH	Rail	
None	28.50	30.31	41.2	27.54%	26.37	27.04	46.60	23.97%	31.51	26.47	42.02	20.76%
Road costs (-10%)	28.49	30.32	41.19	27.91%	26.36	27.06	46.58	24.29%	31.51	26.47	42.02	21.11%
Rail costs (-20%)	1.21	32.88	65.91	33.83%	21.29	28.10	50.61	36.87%	19.36	27.30	53.35	31.35%
Road taxes (+20%)	28.50	30.31	41.19	26.40%	26.37	27.04	46.60	23.01%	31.51	26.47	42.02	19.67%
Freight demands (+15%)	30.28	29.87	39.86	28.21%	25.77	27.71	46.52	23.73%	30.48	27.22	42.30	21.06%
All	0.60	33.04	66.36	33.13%	19.27	28.84	51.89	35.60%	18.73	27.78	53.49	30.92%

Table 8: Results of the best-case scenario analysis

Brotcorne, L., Labbé, M., Marcotte, P., and Savard, G. (2000). A bilevel model and solution algorithm for a freight tariff-setting problem. *Transportation Science*, 34(3):289–302.

Brotcorne, L., Labbé, M., Marcotte, P., and Savard, G. (2001). A bilevel model for toll optimization on a multicommodity transportation network. *Transportation Science*, 35(4):345–358.

Brotcorne, L., Labbé, M., Marcotte, P., and Savard, G. (2008). Joint design and pricing on a network. *Operations research*, 56(5):1104–1115.

Caris, A., Macharis, C., and Janssens, G. K. (2013). Decision support in intermodal transport: a new research agenda. *Computers in Industry*, 64(2):105–112.

Carreira, J., Santos, B., and Limbourg, S. (2012). Inland intermodal freight transport modelling. *ETC Proceedings*.

Community of European railway and infrastructure companies (2016). Longer trains: Facts and experiences in europe. results of the cer working group on longer and heavier trains.

Crainic, T., Ferland, J.-A., and Rousseau, J.-M. (1984). A tactical planning model for rail freight transportation. *Transportation science*, 18(2):165–184.

Crainic, T. G. (2000). Service network design in freight transportation. *European Journal of Operational Research*, 122(2):272–288.

Crevier, B., Cordeau, J.-F., and Savard, G. (2012). Integrated operations planning and revenue management for rail freight transportation. *Transportation Research Part B: Methodological*, 46(1):100–119.

Erera, A., Hewitt, M., Savelsbergh, M., and Zhang, Y. (2013). Improved load plan design through integer programming based local search. *Transportation Science*, 47(3):412–427.

European Commission (2007). Customer-driven rail-freight services on a european mega corridor based on advanced business and operating models (cream), integrated project, european commission, directorate general dg vii, 6th eu framework programme, brussels, belgium.

European Commission (2011). Transport white paper: roadmap to a single european transport area – towards a competitive and resource efficient transport system.

European Commission (2015). *North Sea Baltic - Work plan of the European coordinator Catherine Trautmann.*

European Commission (2016a). Eu transport in figures. statistical pocket book 2016.

European Commission (2016b). Evaluation of regulation (eu) 913/2010 concerning a european rail network for competitive freight.

European Commission (2017). Rfc north sea-baltic corridor information document - book 1: Generalities timetable 2017.

European court of auditors (2016). Special report: Rail freight transport in the eu: still not on the right track.

European Environment Agency (2007). Size, structure and distribution of transport subsidies in europe.

Federal ministry of transport and digital infrastructure (2017). Rail freight masterplan.

Friedlaender, A. F. and Spady, R. H. (1981). *Freight transport regulation.* Mit Press Cambridge, Mass.

Gilbert, F., Marcotte, P., and Savard, G. (2014). Mixed-logit network pricing. *Computational Optimization and Applications*, 57(1):105–127.

Gilbert, F., Marcotte, P., and Savard, G. (2015). A numerical study of the logit network pricing problem. *Transportation Science*, 49(3):706–719.

Infrabel (2016). Document de référence du réseau.

Janic, M. (2008). An assessment of the performance of the european long intermodal freight trains (lifts). *Transportation Research Part A: Policy and Practice*, 42(10):1326–1339.

Kimes, S. E. (1989). Yield management: a tool for capacity-considered service firms. *Journal of operations management*, 8(4):348–363.

Kreutzberger, E. (2003). Impact of innovative technical concepts for load unit exchange on the design of intermodal freight networks. *Transportation Research Record: Journal of the Transportation Research Board*, (1820):1–10.

Kreutzberger, E., Macharis, C., Vereecken, L., and Woxenius, J. (2003). Is intermodal freight transport more environmentally friendly than all-road freight transport? a review. In *nectar conference*, number 7, pages 13–15.

Labbé, M., Marcotte, P., and Savard, G. (1998). A bilevel model of taxation and its application to optimal highway pricing. *Management science*, 44(12-part-1):1608–1622.

Labbé, M. and Violin, A. (2013). Bilevel programming and price setting problems. *4OR*, 11(1):1–30.

Li, L. and Tayur, S. (2005). Medium-term pricing and operations planning in intermodal transportation. *Transportation science*, 39(1):73–86.

Liu, D. and Yang, H. (2015). Joint slot allocation and dynamic pricing of container sea–rail multimodal transportation. *Journal of Traffic and Transportation Engineering (English Edition)*, 2(3):198–208.

Marcotte, P., Savard, G., and Schoeb, A. (2013). A hybrid approach to the solution of a pricing model with continuous demand segmentation. *EURO Journal on Computational Optimization*, 1(1-2):117–142.

Mersha, A. G. and Dempe, S. (2006). Linear bilevel programming with upper level constraints depending on the lower level solution. *Applied Mathematics and Computation*, 180(1):247–254.

Mostert, M. and Limbourg, S. (2016). External costs as competitiveness factors for freight transport—a state of the art. *Transport Reviews*, 36(6):692–712.

Newton, S. (2009). Deliverable 7. freight flows final. worldnet project (worldnet. worldwide cargo flows) deliverable 7. *Funded by the European Community under the Scientific Support to Policies (Framework 6), http://www. worldnetproject. eu/documents/Public D*, 7.

Phillips, R. L. (2005). *Pricing and revenue optimization*. Stanford University Press.

Schroten, A., Van Essen, H., Otten, M., Rijkee, A., Schreyer, C., Gohel, N., Herry, M., and Sedlacek, N. (2011). External and infrastructure costs of freight transport paris-amsterdam corridor. part 1. overview of cost, taxes and levies. Technical report, CE Delft.

Stackelberg, H. v. (1952). *Theory of the market economy*. Oxford University Press.

Tawfik, C. and Limbourg, S. (2018). Pricing problems in intermodal freight transport: Research overview and prospects. *Sustainability*, 10(9):3341.

Troch, F., Vanelslander, T., Belboom, S., Léonard, A., Limbourg, S., Merchan Arribas, A., Mostert, M., Pauwels, T., Vidar, S., and Sys, C. (2015). Brain trains: Intermodal rail freight transport and hinterland connections a swot analysis to assess the belgian rail practice.

Troch, F., Vanelslander, T., Belboom, S., Léonard, A., Limbourg, S., Merchan Arribas, A., Mostert, M., Pauwels, T., Vidar, S., and Sys, C. (2017). A road map for explorative scenario creation on belgian rail freight transport development. *Competition and Regulation in Network Industries*, 18(1-2):3–21.

Vieira, L. F. M. (1992). *The value of service in freight transportation*. PhD thesis, Massachusetts Institute of Technology.

Wang, Y., Bilegan, I. C., Crainic, T. G., and Artiba, A. (2016). A revenue management approach for network capacity allocation of an intermodal barge transportation system. In *International Conference on Computational Logistics*, pages 243–257. Springer.

Wieberneit, N. (2008). Service network design for freight transportation: a review. *OR spectrum*, 30(1):77–112.

Ypsilantis, P. (2016). *The Design, Planning and Execution of Sustainable Intermodal Port-hinterland Transport Networks*. PhD thesis, Erasmus University Rotterdam.

Ypsilantis, P. and Zuidwijk, R. (2013). Joint design and pricing of intermodal port-hinterland network services: Considering economies of scale and service time constraints. Technical report.