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Scenario-based analysis for intermodal transport in the context of service network design models

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ABSTRACT

In this paper, we discuss service network design models for consolidation-based freight transport systems. Two path-based formulations are presented for the domestic and long-corridor cases, respectively. In the context of intermodal transport as a relevant application, the modelling frameworks are applied in Belgium-related case studies, in order to draw meaningful managerial insights. Several future scenarios are experimented by analysing a number of parameters that have been identified as significant operational factors and policy levers. The results underline the costly position of rail transport and a clear economic favouring of inland waterways (IWW), potentially attributed to the high rail fixed costs. Additionally, it is suggested that intermodal transport can benefit from rail subsidies, especially during the early stages of covering the market. Even in the best-case scenario, the resulting modal shares are far from reaching the figures desired for freight transport in the EU. Thus, more powerful instruments need to be implemented to promote greener transport schemes.

1. Introduction

Modal efficiency is an essential factor for the realization of world and continental trade activities, where optimizing the use of transport modes with high capacity is a crucial issue. Nevertheless, in Europe, there is still a great imbalance in modal split on land with 71.7% of the EU freight transport still taking place via road (European Commission, 2017). Environmentally, Greenhouse Gas (GHG) emissions from EU transport, excluding international maritime, represented about 23% of the total EU emissions in 2014, compared to 15% in 1990 and 20% in 2000 (European Commission, 2016). In terms of energy consumption, transport is the highest sector in this respect in the EU-28 and the second in Belgium with a 31.7% and 28% of the final energy consumption in the year 2012, respectively (Merchan Arribas et al., 2017).

In this sense, *intermodal transport* is considered as a transport scheme with significantly high potentials to endorse sustainability and energy efficiency. It could be defined as a multimodal chain of transport services that links an initial shipper with the final consignee of the shipment, where the goods are moved, in one and the same loading unit (typically containers, swap bodies or vehicles), without being handled when changing modes at designated terminals/hubs (European conference of ministers of transport, 1997). Generally, environment-friendly transport modes, such as rail or IWW, are being used for most of the travelled route, known as the *main haulage*, and road for the shortest possible parts, to and from the origin and destination terminals respectively, known as the *pre- and post-haulage (PPH)* or *drayage operations*.

Owing to its environmental advantages and the opportunities it provides to generate economies of scale (Crainic et al., 2018; Demir et al., 2016; Kreutzberger, 2003; Kreutzberger et al., 2003; Mostert and Limbourg, 2016), intermodal transport has drawn a wide interest in the scientific and political community. This is clearly manifested, for instance, in the roadmap set by the European Commission (2011) to shift 30% of road freight over 300 km to less environmentally harmful modes by the year 2030, and more than 50% by 2050. These goals represent the main framework of the research project BRAIN-TRansversal Assessment of Intermodal New Strategies

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(BRAIN-TRAINS, 2014), to which this work belongs. The main goal of the project is to develop a blue print establishing the detailed criteria and conditions for developing an innovative international intermodal network in Belgium, as part of the Trans-European Transport Network (TEN-T).

Along this objective, this paper addresses the tactical problem of service network design for consolidation-based transport systems - in particular, intermodal transport. The contribution is two-fold. First, methodologically, we present tactical network design models within the intermodal context, where we combine the relevant minimum utilization and resource balancing constraints, as well as introduce a special procedure to construct intermodal itineraries. To the best of our knowledge, this is the first tactical network design model for intermodal transport that represents flow-balancing requirements as round-trip constraints, in combination with minimum service utilization as hard constraints. Second, within an innovative future scenario-analysis framework, we apply the developed models on practical case studies related to Belgium, in order to draw relevant logistics management insights that could contribute to stimulating sustainable freight transport in Europe. We start by studying two modelling approaches that are relevant for domestic and long-corridor cases, respectively. A path-based multicommodity formulation is initially introduced, considering integral design variables and itinerary-based routing decisions. The problem depicts a cost-minimization objective, from the medium-term economic perspective of a transport operator. The model is later developed for the long-distance case, by further defining the services by their dispatch day and imposing round services' constraints as a form of resource balancing.

In the quest of studying the future developments of intermodal transport and providing insights into strengthening its position, a scenario-based analysis framework is devised as a risk analysis technique and a tool for decision-making. Based on the definitions in Kahn and Wiener (1967), Lobo et al. (2005), a scenario is interpreted in our research context as an exploration of hypothetical future events and their complex interactions, without attempting to forecast the exact nature of the future. The considered elements are required to be plausible and consistent. Based on an approved analysis of the current strengths, weaknesses, future trends and barriers for intermodal transport, three scenarios, corresponding to three outlooks on the future - best, worst and average cases - are developed. In order to avoid subjective interpretations, it is crucial that the outlined scenario elements are validated by a heterogeneous panel of experts through a defined process, as it will be later explained. The scenario parameters are mathematically examined by the means of the developed service network design models, essentially from a cost assessment perspective. The models are invoked on real-world data instances, with a strong emphasis on freight transport in and through Belgium. The potential correlations between the foreseen changes in the transport modes' operating costs, market demands and road taxes, on one side, and the competitiveness of intermodal transport, on the other, are thoroughly investigated. The three transport modes - road, rail and IWW - are considered for these experiments. Important managerial insights are drawn from the results with respect to the modal cost partition and the necessity of rail subsidies, as well as relevant recommendations to enhance the future position of intermodal transport in Europe. Further environmental assessment is applied on the domestic Belgian case for the different scenarios and with applying a chosen threshold of rail subsidies, based on the Life Cycle Assessment methodology (LCA) discussed in Merchan et al. (2019) to evaluate the values of externalities. In particular, we measure the environmental impact of each case in terms of the output GHG emissions and energy consumption, with respect to a reference unit of flows calculation on the different transport modes.

The remainder of the paper is organized as follows. In Section 2, we provide a comprehensive review of the state of the relevant literature, as well as formulate the problem scope. In Section 3, we present the two formulations of the service network design model and cover its building components in details. The scenario-based framework is introduced in Section 4, as well as the involved hypotheses. The computational results that are related to the two considered case studies are discussed in Section 5. Section 6 presents the environmental assessment in relation to the developed scenarios for the Belgian case study. Finally, closing remarks are given in the last section along with potential future perspectives.

2. Background and scope

Classically, the literature differentiates between freight transport operations over long distances, such as rail, full truckload and less-than-truckload (LTL), and those that perform multiple pick-up and delivery operations, mainly by truck, over short distances. The former case is often referred to as the *service network design* problem, while the latter is identified as the *vehicle routing* problem, as noted by Crainic and Laporte (1997). While the decisions of demands' routing are relevant for both categories, the issue of freight consolidation becomes particularly central for tactical service network planning, as demands of multiple customers simultaneously share the same 'vehicle'. In this case, carriers performing transport services for various shippers are additionally entitled to make frequency and scheduling decisions. 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).

Several assets (alternatively, resources) are involved in operating services, e.g., tractors, locomotives, trailers, loading/unloading units and crews. They are available at costs and with limited quantities, which requires, in most cases, an optimal management. Design-balance constraints are typically used to balance the number of asset units entering and leaving each terminal/node. Arc- and cycle-based formulations are usually considered, within a time-dependent service network design problem. Pedersen et al. (2009) consider generic service network design models with asset balance constraints. A tabu search metaheuristic framework for the arc-based formulation is developed and experimented on a set of benchmark instances. Andersen et al. (2009a) show, by a computational study, that the formulations based on cycle design variables may be solved faster than the formulations based on arc design variables. Bai et al. (2012) examine various mechanisms within a guided local search framework to reduce the computational time while Andersen et al. (2011) study a branch and price method. Bai et al. (2014) investigate a stochastic service network design problem with rerouting. In Bai et al. (2015), a service network design formulation is exploited to obtain the lower bound of a multi-shift full truckload transportation problem. A hub-and-spoke structure for air cargo express delivery service network design problem is studied in Barnhart et al. (2002), Kim et al. (1999); and Armacost et al. (2002). Service network design also exists in other types of transportation systems, for example ferry service network design (Lai and Lo, 2004; Wang and Lo, 2008), and, in a more limited presence for land-based transport carriers (e.g., Andersen et al., 2009b; Lin et al., 2012; Perennes, 2014; Teypaz et al., 2010).

In what concerns the intermodal transport literature, the first developed multi-modal network models that were able to handle intermodal flows appeared in the early 1990s (Caris et al., 2013). Since then, the terminal design and infrastructure network configuration have particularly received an increased attention (Caris et al., 2008). Geographic information system (GIS)-based decision support models have also been developed to test the impact of different policy measures on the stimulation of intermodal transport (e.g., introducing new terminals and subsidies in Macharis and Pekin, 2009 and increasing fuel prices and internalising external costs in Macharis et al., 2010). More recently, SteadieSeifi et al. (2014) noted that tactical-level issues have been accorded a high interest; these problems typically involve an optimal utilization of the given infrastructure by choosing services and associated transport modes, allocating their capacities to orders, and planning their itineraries and frequency. Nevertheless, there is an observable gap in optimization-based approaches in tactical/medium-term intermodal transport planning topics, such as network design and pricing problem as pointed by Tawfik and Limbourg (2018). In particular, to the best of our knowledge, there is a potential room in the intermodal literature for service network design frameworks that properly and simultaneously model the relevant logistics features (e.g., capacity utilization in long hauls, resource balancing, correct intermodal path structures, etc.).

In this paper, we aim to address this gap through service network design modelling and scenario-based analysis, in order to gain insights about the influence of the costs and other relevant operational parameters and political levers on the repartition of the flows and modal split over a freight transport network. Formally, the problem belongs to the tactical decision horizon, tackling medium-term planning issues from the economic perspective of a typical transport operator. The market is assumed to be composed of shippers with demands to be delivered over the network. The decisions are two-fold: the operating frequencies of the services during the planning period - typically, a week - and the optimal routing of the demands over service-based itineraries. The objective is to deliver the demands in a cost-minimization manner, where the costs are divided into a fixed and a variable component to run the services and transport the goods over them, respectively. The model is designed to suit a general consolidation-based multimodal framework; a service is defined by a transport mode, in addition to its origin-destination node pair, and thus corresponds to a physical arc in the network. Mathematically, the proposed mixed-integer program extends the classical static path-based multicommodity formulation, originally introduced in Crainic (2000) in the general freight transport context, and later re-considered in Crainic and Kim (2007) for intermodal transport. A static case is assumed throughout the decision process, in terms of the shipping demands, as well as the underlying physical network, including the terminals' locations. The time factor is considered in terms of scheduled services for the modelling approach addressing long-corridor aspects. However, a decision is taken not to consider a time-expanded formulation, in the sense of avoiding the replication of the physical nodes of the network for each time period, and thus not representing holding service arcs that link consecutive time realizations of the same physical node. Similarly, a simplification is assumed with respect to the design variables, where a cycle-based formulation is not considered, thus restricting the representation of some asset-related requirements, such as the length of the asset routes. The reasons behind these decisions are to respect the medium-term horizon and to avoid modelling complications at the later stage when pricing decisions will be integrated. Finally, the developed mathematical frameworks are utilized within a scenario-analysis methodology, where previously identified and validated parameters and policy levels are put to the test against three possible outlooks on the future. Relevant cost correlations are identified and related recommendations are proposed with respect to stimulating sustainable transport in the European market.

3. Service network design modelling

In this part, two variants of the model will be discussed, for the domestic and long-distance cases; they will be referred to as SND and SND-LD, respectively. The models essentially differ in their definition of the services and their consideration of a form of resource-balancing constraints. The main components of the modelling framework are outlined in details.

3.1. Itineraries' generation

In the considered problem, it is assumed that the intermodal paths, represented in service-based itineraries, have been generated *a priori* for all the commodities. 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. 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 transportation services, where each service $s \in \mathcal{S}$ is defined by a physical arc $a_s \in \mathcal{A}$ in the network, a transport mode m_s (i.e., road, rail or IWW) and maximum allowed units of capacity u_s. A set of commodities $\mathcal{K}$ are travelling the network, where each commodity $k \in \mathcal{K}$ is assigned an origin and destination pair $(o_k, d_k) \in \mathcal{N} \times \mathcal{N}$. The terminology of a commodity is used in the sense of a shipping demand, in order to follow the nomenclature convention of the multicommodity network design formulations, to which our developed models belong. Therefore, we do not differentiate between the type of the transported goods. Given such a network representation, a set of services and commodities, a procedure is designed with the aim of generating all feasible paths for each commodity's origin-destination pair. Feasibility is meant in the sense of being geographically correct, as well as conforming to an intermodal-related path structure as it will be later explained.

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 assumed to be found and added to its set of feasible itineraries. The details of this procedure are described in Algorithm 1.

Within the procedure to generate a typical itinerary, the following conditions are respected:

- No node is being visited more than once along a certain path; cycles are avoided.
- No two consecutive services are performed by road; if it is the case, the two services are replaced by a single road service.
- The length of an intermodal path should exceed its equivalent all-road distance by a certain allowed margin.

Further conditions could equally be applied concerning the length of the PPH services with respect to the long-haul service, to ensure that the significant part of the intermodal itinerary is not performed by road. The generated list of itineraries for each commodity is then considered throughout the model as the basis of the routing decisions.

Algorithm 1. The itineraries' generation procedure.

```
procedure BuildPaths
    Max ← Maximum no. of services in an itinerary
    CommList ← List of commodities
    for each c ∈ CommList do
        o ← Origin node of c
        d ← Destination node of c
        L^c ← New empty list of itineraries of c
        for each service s leaving o do
            n ← Destination node of s
            P ← New empty itinerary
            L^c ← Concatenate(L^c, result of BuildPathHelper(n, d, Max − 1, P))
        end for
    end for
end procedure
procedure BuildPathsHelper(Node, Dest, Length, Path)    ▷ A helper recursive procedure to generate feasible paths
    L ← New empty list of itineraries
    if Node = Dest then
        Append Path to L
    else
        if Length > 0 then
            for each service s leaving Node do
                n ← Destination node of s
                TempPath ← Result of appending s to Path
                L ← Concatenate(L, result of BuildPathHelper(n,
                Dest, Length − 1, TempPath))
            end for
        end if
    end if
    return L
end procedure
```

3.2. SND formulation

Let f_s be a fixed cost of operating service $s \in \mathcal{S}$ once in the planning period, typically one week. Additionally, for each commodity $k \in \mathcal{K}$, we consider a total of demand volumes w^k in tonnes, a variable cost v_s^k to transport one tonne of commodity k using service s and a minimum fraction q^k of its demand that should be sent over any of its used itineraries. In other words, if an itinerary of a freight demand k is to be open for use, at least q of this demand has to be sent over this itinerary. This parameter is used to define a set of hard constraints, referred to as minimum utilization constraints, to serve two purposes:

- To ensure that an itinerary has a minimum required level of utilization; thus contributing to the cost minimization perspective.
- To prevent the split of the demands over a high number of itineraries; thus minimizing the chances of potential freight losses and delays.

At a pre-processing stage, a set of feasible intermodal itineraries $\mathcal{L}^k$ are generated using the above Algorithm 1 for each commodity k, where each itinerary $l \in \mathcal{L}^k$ is tantamount to a sequence of services ($l \subseteq \mathcal{S}$). Moreover, additional parameters δ_s^l are introduced for each service $s \in \mathcal{S}$ and itinerary $l \in \mathcal{L}^k$ of commodity $k \in \mathcal{K}$, in order to link the services to their corresponding itineraries in the path-based model; $\delta_s^l = 1$, if service s is used within itinerary l (0, otherwise). Three sets of variables are defined: y_s denoting the discrete frequency of running service s in a week, h_l^k denoting the volumes of commodity k shipped on itinerary l and the binary variables $\bar{h}_l^k$ taking the value 1 whenever some flows are sent over the corresponding itinerary ($h_l^k > 0$) and 0 otherwise.

Based on the above notation, the service network design problem can be expressed as a mixed-integer programming (MIP) formulation as follows:

(SND)

$$\min_{y,h,\bar{h}} \quad \sum_{s\in\mathcal{S}} f_s y_s + \sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}^k} \sum_{s\in\mathcal{S}} \delta_s^l v_s^k h_l^k \tag{1a}$$

$$\text{s.t.} \quad \sum_{l\in\mathcal{L}^k} h_l^k = w^k \quad \forall k \in \mathcal{K}, \tag{1b}$$

$$\sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}^k} \delta_s^l h_l^k \le u_s y_s \quad \forall s \in \mathcal{S}, \tag{1c}$$

$$h_l^k \le w^k \bar{h}_l^k \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{1d}$$

$$q^k w^k \bar{h}_l^k \le h_l^k \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{1e}$$

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

$$h_l^k \ge 0 \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{1g}$$

$$\bar{h}_l^k \in \{0, 1\} \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k \tag{1h}$$

where the objective function (1a) denotes a minimization of the fixed costs of offering the transport services and the variable costs of shipping the actual demands using these services. In addition to the defined ranges of the variables in constraints (1f)–(1h), the remainder of the formulation describes necessary conditions. Constraints (1b) dictate that the total demands should be satisfied and delivered over the offered itineraries. Constraints (1c) state that the services' capacities are not to be exceeded by the transported volumes. Finally, constraints (1d)–(1e) establish a minimum utilization over the itineraries, ensuring that an itinerary is not to be used unless the minimum fraction q^k of the commodity's demand is sent over it.

3.3. SND-LD formulation

In addition to the above model, an extension has been developed to account for long-distance related aspects. To better represent this goal, the model builds upon the previous formulation to represent a scheduled service network design problem, prescribing the day for each service dispatch and ensuring a balance of resources at the terminals.

In this formulation, a service will be further defined by its dispatch day $t \in \{0,..,6\}$, referring to each day of the week and, hence, uniquely represented as a couple (s,t), where $s \in \mathcal{S}$. The corresponding frequency variables y_s^t and path linking parameters δ_s^{lt} will be updated accordingly. Furthermore, in order to represent the resource balancing requirement, an additional of services' couples $\mathcal{S}_{return}$ is defined, where $\mathcal{S}_{return} = \{((s_1,t_1),(s_2,t_2))|s_1,s_2 \in \mathcal{S} \quad \text{and} \quad t_1,t_2 \in \{0,..,6\}\}$. Its main idea is to group in *couple-form*, for each outward long-haul service $s_1 \in \mathcal{S}$ (i.e., rail or IWW), its equivalent return service $s_2 \in \mathcal{S}$ using the same train/vessel. A return service is meant in the sense of a service to be dispatched back on the following day of the outward journey's arrival day; i.e., let t_1 be the dispatch day of service s and d_s its transit time, the return service of s will then be dispatched from the destination point of s on day t_2, where $t_2 = (t_1 + d_s + 1)\text{mod}7$. These return services are not restricted to be empty as they, too, belong to the same set of services; their operating costs are not different to those of the outward journey. Therefore, it is in the economic interest of the service operator - the decision maker - to seek to achieve a high load factor of the return services, depending on the demand situation. The below updated MIP formulation is then obtained:

(SND-LD)

$$\min_{y,h,\bar{h}} \quad \sum_{s\in\mathcal{S}} \sum_{t\in\{0,..,6\}} f_s y_s^t + \sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}^k} \sum_{s\in\mathcal{S}} \sum_{t\in\{0,..,6\}} \delta_s^{lt} v_s^k h_l^k \tag{2a}$$

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

$$\sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}^k} \delta_s^{lt} h_l^k \le u_s y_s^t \quad \forall s \in \mathcal{S}, \forall t \in \{0,..,6\}, \tag{2c}$$

$$h_l^k \le w^k \bar{h}_l^k \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{2d}$$

$$q^k w^k \bar{h}_l^k \le h_l^k \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{2e}$$

$$y_{s_1}^{t_1} = y_{s_2}^{t_2} \quad \forall ((s_1,t_1),(s_2,t_2)) \in \mathcal{S}_{return}, \tag{2f}$$

$$y_s^t \in \mathbb{Z}^* \quad \forall s \in \mathcal{S}, \forall t \in \{0,..,6\}, \tag{2g}$$

$$h_l^k \ge 0 \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k, \tag{2h}$$

$$\bar{h}_l^k \in \{0,1\} \quad \forall k \in \mathcal{K}, \forall l \in \mathcal{L}^k \tag{2i}$$

In addition to the carried on constraints from the previous model, the set of resource balancing constraints (2f) ensure that each dispatched long-haul service will have to be indeed returned to its departure point. The two developed formulation, SND and SND-LD, will be used as the basis of the scenario analysis of intermodal transport, for the domestic and the long-distance cases, respectively.

3.4. Services' subsidies

The developed models allow for the possibility of testing the variations in the key considered parameters: cost changes and evolution demand volumes. In particular, an interesting outlook would be to probe the effect of subsidizing freight-carrying services from external funds on the flow repartition over the transport modes. This can be achieved through a small modification in the respective objective function. A subsidy parameter β is generally defined by monetary unit per unit of distance. Let n_s be the distance over which service s runs. The modified objective of the SND model will be as follows:

$$\min_{y,h,\bar{h}} \quad \sum_{s\in\mathcal{S}} f_s y_s + \sum_{k\in\mathcal{K}} \sum_{l\in\mathcal{L}^k} \sum_{s\in\mathcal{S}} \delta_s^l v_s^k h_l^k - \sum_{s\in\mathcal{S}} \beta n_s y_s \tag{3a}$$

The objective of the SND-LD model could be modified in the same way.

4. Scenario-based framework

The notion of a *scenario* is used throughout this work with the interpretation of offering insights into the future, without attempting to forecast its exact nature. The main research goal is to identify the key factors contributing to the development of intermodal freight transport and to measure the impact of the decisions altering these key factors in the future. The literature review conducted within the project BRAIN-TRAINS (Troch et al., 2015, 2017) shows that there is no existing methodology that can be applied to translate a surveyed list of internal characteristics and possible external trends of a certain subject into quantified scenarios. Therefore, an existing tool, such as the *Delphi* technique (Hsu and Sandford, 2007), is used in order to design such a development path.

The Delphi technique is a process where a heterogeneous panel of experts discusses and validates the presented results, until a consensus is acquired. In the current research, this panel consists of port authorities, rail freight companies, government representatives, academic contributors and private intermodal transport users. The full panel of experts can be seen on the project's official page (BRAIN-TRAINS, 2014). The process consists of several iterations in order to converge the different opinions. In our project's adaptation of this process, we start by a round of consultation comprising a draft Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis: a preliminary list of possible internal and external characteristics related to the subject of intermodal transport. This draft is a result of a research of existing literature and published studies, as well as of different field interviews. In order to validate these previous results, individual interviews, as well as round-table discussions are conducted during the second and the third round, respectively. A questionnaire can eventually be formulated containing the final SWOT elements. Respondents scored each of the elements on a Likert scale, measuring the impact and the likelihood of happening for each element. In this way, the importance of each element, as well as the level of uncertainty, can be obtained. The output of this survey is analysed in order to obtain a priority ranking of the elements for each SWOT category, which eventually helps as an input to build the plausible future scenarios for further analysis. Troch et al. (2015, 2017) provide a full description of this development path from the SWOT analysis to the scenario creation. The survey methodology is discussed as well, in terms of the Likert scale definition, the calculation of the frequency tables as common indicators for the data analysis, as well as the process of obtaining the final priority ranking. The interested reader is invited to check the project's official page (BRAIN-TRAINS, 2014) for the full list of deliverables.

The finally ranked elements of the SWOT are translated into a selection of scenario parameters and corresponding values, containing the most plausible future events affecting the development of intermodal transport in and through Belgium. The parameters quantification is performed according to three levels: best-, worst- and middle-case scenario (Troch et al., 2017). The definitions are in a direct linkage to the goals set by the White Paper of the European Commission (2011). A point of reference is taken for the period 2010–2015, while scenario values are taking into account a scenario horizon of 2030. Following the Delphi exercise, another round of validation is performed among the experts in order to approve the values of the different scenario elements. From an Operational Research perspective, we design the computational experiments in such a way as to invoke parametric analyses and practically probe the impact of the different changes in policies and operational circumstances - as described in each scenario - on the future success of intermodal transport. The mathematical models designed in Section 3 are taken as rational reasoning layouts for this process.

In what follows, the parameters' choices relative to each scenario are discussed, as well as the additional operational hypotheses that are assumed throughout the experiments.

4.1. Scenario parameters

In accordance to the goals set by the White Paper by the European Commission (2011), the best-case scenario is designed to be in line with the first desired 30% modal shift from road to less environmentally harmful modes by the year 2030, carried by both the government and the transport sector. The worst-case scenario reflects the situation if this objective is not aspired. Contrary to the two previous extreme cases, the middle-case scenario is considered as an in-between scenario, where the White Paper's goal is still carried on from the best case, however not required to be completely reached by 2030.

Based on the realized SWOT analysis, the results are translated into a selection of crucial scenario elements and their corresponding parameters and values. This selection process is performed over two steps. First, the SWOT parameters having a high importance are determined as structural elements. Second, based on the level of control over these elements and the certainty about them, they are being identified to be used as strategic levers or explorative factors during the scenario creation. Measurable parameters and corresponding values are, finally, formulated for the different selected SWOT elements. The selection and the output validation were performed by the panel of experts of the BRAIN-TRAINS project according to a so-called *Delphi* technique, often used to acquire consensus within a heterogeneous panel of experts as explained in Troch et al. (2017). In an *input-output* framework, Table 1 shows the considered scenario inputs from the operational perspective, among the total list of scenario parameters, together with their calculated reference-, best-, worst- and middle-case values. The envisaged output from the mathematical models is essentially the computed modal split, in terms of the percentage of tonne-kilometre (tkm). The transport modes considered for this analysis are road, rail and IWW.

The infrastructure and maintenance costs, as stated in Schroten et al. (2011), comprise: the construction costs, the maintenance and operational costs and the land use costs. The study further provides a fixed and variable parts division of the costs for each transport mode. For this parameter the comparison is made between rail and IWW transport, instead of road transport. For the latter, infrastructure is heavily used by citizens and therefore constructed and maintained by the government, as a public service. Up until recently, road freight transport could use this infrastructure without additional charges. However, this situation has already started to change through tax implementation and future plans are envisaged to better develop these figures so as to reflect the actual economic and social implications of using the road. This factor is represented by the parameter 'road taxes'. As rail and IWW are competitors for sustainable transport, it can be seen from Table 1, that IWW has an advantage in terms of infrastructure and maintenance costs. In the best-case scenario, rail costs are assumed to undergo a greater decrease than those of the road and IWW; their evolution in the other scenarios are uniform for the three transport modes.

The reference road taxes values are calculated based on the updated values of the Viapass tax in Belgium, corresponding to the average existing rates weighed by the number of vehicles in each category for 2014 (EMISIA, 2014). The general belief is that the transport demands are steadily rising in the future, as a consequence to the economic growth (Bureau fédéral du Plan, 2019). The evolution of the 'freight demands' parameter in the scenarios reflects the respective opportunities for freight consolidation and the shift towards intermodal transport. This parameter is captured by the Origin-Destination (O-D) matrix that is considered as an input in the experiments.

4.2. Additional hypotheses

In addition to the above stated parameters, other elements are considered as well to establish necessary operational hypotheses. It is important to clarify that the underlying physical network is considered fixed throughout the experiment in terms of the geographical information regarding the origin-destination node positions, the physical connection distances and the terminal locations. As our developed models are tactical (medium-term) decision frameworks, those previous strategic decisions are beyond the scope of our calculations. The geographical division is based on the notion of the NUTS classification (Nomenclature of territorial units for statistics): a hierarchical system for dividing up the economic territory of the EU. Based on a socio-economic analysis, the classification lists regions at three levels, with NUTS 1 being major socio-economic regions, NUTS 2 basic regions for the application of regional policies and NUTS 3 small regions for specific diagnoses (European Union, 2015). For the following experiments, two outlooks are considered: NUTS 3 level for the Belgian domestic view and its neighbouring nodes (case study I) and NUTS 2 level for the freight corridors over long distances (case study II). The transport networks are the ones available at Eurostat (for details, see Carreira et al., 2012). Regarding the Belgian case, the available data at the NUTS 2 level have been disaggregated to a NUTS 3 level within Belgium, using the number of companies of productive sectors in these regions as the proxy indicator.

The list of the additional inputs is essentially composed of:

- **Terminals' physical locations**: Besides the major hinterland terminals according to the Agora Intermodal Terminals database (2018), the sea terminals (Antwerp, Zeebrugge and Ghent) are taken into account since they have both rail and IWW connections. Two cases are considered. First, at the national Belgian level, the locations are defined at the NUTS 3 level, as directly available in the database. Second, at the whole European level, the locations are aggregated with respect to the NUTS 2 level. Table 2 lists the different considered terminals at the European level, along with their type: rail terminal, IWW terminal or both combined.
- **Transport modes' capacities**: Average cases are assumed for the three considered transport modes, based on the standard acknowledged capacities. Namely, 24 tonnes, 1500 tonnes and 3000 tonnes are considered as a unit capacity for the road, rail and IWW modes, respectively.
- **Transport modes' distances**: Regarding rail and road networks, distances between each pair of supply/demand nodes or intermodal terminals are the shortest paths in distance. The

Table 1
Scenario input parameters.

Parameter	Reference value	Best-case value	Worst-case value	Middle-case value
Infrastructure and maintenance costs (Road)	0.00545 €/tkm	−10%	+10%	−5%
Infrastructure and maintenance costs (Rail)	0.0698 €/tkm	−20%	+10%	−5%
Infrastructure and maintenance costs (IWW)	0.0219 €/tkm	−10%	+10%	−5%
Road taxes	0.15 €/km	+20%	+/−0%	+10%
Freight demands	–	+15%	−10%	+5%

IWW network distances are computed based on the Periskal route planning tool (Promotie Binnenvaart Vlaanderen, 2016) networks of transport.

5. Computational experiments

During the following tests, two main market demand views are essentially adopted: a domestic scale, where only national flows within Belgium are considered, as well as between Belgium and its neighbouring nodes, and a European scale, where long-distance freight services are regarded. For the latter case, the three rail freight corridors, passing through Belgium, are taken as a basis for each data instance. The three transport modes - road, rail and IWW - are included in the analysis in both cases. For each considered commodity, alternatively, shipping demand, for which an intermodal itinerary exists, an all-road path is enabled, in order to test the cost-related effects on the resulting modal split. Therefore, the underlying assumption is that the decision-maker in this problem has the possibility to satisfy the shipping demands through intermodal itineraries, all-road paths or a combination of which. This decision is taken from a pure cost-minimization perspective, in the presence of the stated constraints in the mathematical models. Note that all the results are obtained by solving the respective models within at most 1% gap from optimality to guarantee the soundness of the drawn conclusions. Experiments have been run on an Intel Xeon CPU ES-2620, 2.10 GHz 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. All the results of the experiments are obtained within a maximum runtime of 15 min. The largest instance on which those experiment metrics hold is Instance 0 with 438 shipping demands and 88 nodes. It is a fully connected and directed graph considering - at least - the road connections, which leads to a number of arcs in this instance that is greater than or equal $(88)*(88-1) = 7656$ arcs. The rail and IWW connections certainly increase this figure. Despite the large size of the considered instance, the solver CPLEX was able to land a nearly optimal solution. This means that for the considered instances of interest, a special solution algorithm is not necessary for this case study.

Table 2
Terminals locations at the European level.

NUTS 2 code	Region name	Rail terminal	IWW terminal
BE10	Brussels-Capital	✓	✓
BE21	Prov. Antwerpen	✓	✓
BE23	Prov. Oost-Vlaanderen	✓	✓
BE33	Prov. Liège	✓	✓
DE11	Stuttgart	✓	✓
DE12	Karlsruhe	✓	✓
DE21	Oberbayern	✓	
DE22	Niederbayern	✓	
DE23	Oberpfalz	✓	
DE25	Mittelfranken	✓	✓
DE26	Unterfranken	✓	✓
DE40	Brandenburg	✓	
DE50	Bremen		✓
DE60	Hamburg	✓	✓
DE80	Mecklenburg-Vorpommern	✓	
DE92	Hannover	✓	
DEA1	Düsseldorf	✓	✓
DEA2	Köln		✓
DED2	Dresden	✓	
NL33	Zuid-Holland	✓	✓
FR10	Ile de France	✓	✓
FR23	Haute-Normandie		✓
FR30	Nord-Pas-de-Calais	✓	✓
FR42	Alsace	✓	✓
ITC1	Piemonte	✓	
ITC4	Lombardia	✓	
ITF3	Campania	✓	✓
ITF4	Puglia	✓	
ITH5	Emilia-Romagna	✓	
CH03	Northwestern Switzerland	✓	✓
CZ01	Praha	✓	
CZ06	Southeast Poland	✓	
CZ08	Maravan-Silesian	✓	
PL22	Silesian	✓	
PL41	Wielkopolskie	✓	
PL51	Lower Silesian	✓	
LT00	Lithuania	✓	

A special attention is accorded to testing the effects of offering rail subsidies on the subsequent modal split and intermodal transport market share. 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 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 throughout the experiments is on rail transport subsidies that are paid or granted directly from public funds.

5.1. Case study I: Belgium and its neighbours

For the first case study, only the shipping demands between the nodes at the NUTS 3 level in Belgium and its neighbouring countries are considered based on the database of the Worldnet project (Newton, 2009). The data set (Instance 0) consists of a total of 438 commodities and a physical network of 88 nodes. For this set of experiments, the first version of the model SND, that does not account for long-distance aspects, is considered. The different scenario parameters are changed to their respective case values in order to draw conclusions on the flows repartition on the different transport modes, from a costs' perspective. In each of the following tables, the first row corresponds to the results when all the parameters are tuned to the reference scenario. In the subsequent rows, the parameter whose value is changed to the scenario value is referred to, in order to test the effect and significance of each parameter separately. In the last table's row, all parameters' values are changed according to the considered scenario. Based on the resulting flows in tkm per transport mode, the modal split and the market share, corresponding to intermodal and all-road transport, are computed as experiments' outputs. (Table 3) provides the results of the scenario analysis in relation to the Belgian case study (Instance 0).

It is understandable that intermodal transport becomes highly dominated by all-road transport due to the fact that only the flows within and in the neighbourhood of Belgium are considered ($\leq$400 km); a breakeven distance for intermodality's favour is hardly reached. The general remark on the below results is also that, even in the case when intermodal transport is attracting some flows, rail still does not get any shares. This is essentially due to the advantageous cost-related position of IWW with respect to rail, which makes it hard to compensate the operation of a new rail service. The results show as well that the increase in the road taxes has the highest positive effects on diverting the freight flows to intermodal paths. Even though the considered increase is also applicable to the pre- and post-haulage parts of the intermodal chains, its negative effect is more pronounced when the long haul is performed by road. Similarly, the future increase in freight demands creates more opportunities for consolidation and shifting flows from road transport. The tests also show that, in a moderate view of the future (middle-case), the modal split and market share are moving in the favour of IWW-based transport.

Driven by the above negative results with respect to rail-borne flows, the aspect of subsidizing rail services is further put to the test to study its impact on the rail modal shares. The levels of subsidies are represented in terms of fractions of the rail fixed costs, with respect to the reference and middle-case scenarios. The two remaining extreme scenarios are not considered for these tests to avoid drawing biased conclusions.

The first recorded subsidies' levels in Fig. 1 represent the first levels after which rail services start receiving freight flows and their fixed costs become counter-balanced. In both scenarios, the increase in rail flows is quite slow during the first levels of subsidies, up until a certain threshold (65–70 % of the fixed costs, nearly 0.9 €/container) then the change undergoes fast leaps. It is interesting that this level also coincides with the level, after which IWW modal shares experience an opposite decline: diverting flows from IWW to rail is an aspect to be avoided for the sake of the long-term intermodality's success. Nevertheless, the middle-case scenario is slightly dominating the reference case, in terms of both the rail and the IWW shares. This subsidy threshold could also be seen as rendering the rail fixed costs to become around eight times as much as the road fixed costs, thus closing the gap and reducing the rail costs from their original level: around fourteen times as much as the road costs. This result suggests that it is crucial to identify this non-trivial level for each costs' scenario through scientific means in order to be able to make educated decisions in what concerns the business' sustainability and avoiding unnecessary capital spending.

5.2. Case study II: freight corridors through Belgium

In the second case study, the emphasis is essentially on freight services operating over long distances, where consolidation opportunities become more significant. More precisely, the demand flows data regarded for these experiments were obtained from Carreira et al. (2012) at the NUTS 2 level, based on the accessible Worldnet database for Europe (Newton, 2009). Three further instances are defined based on the geographical information provided by RailNetEurope about the rail freight corridors passing through Belgium (Fig. 2), as the market point of interest in the study: namely, the Rhine-Alpine (Corridor 1), the North Sea-Mediterranean (Corridor 2) and the North Sea-Baltic (Corridor 8). The data sets consist of 308 commodities (30 nodes), 160 commodities (21 nodes) and 299 commodities (32 nodes) for Corridor 1, Corridor 2 and Corridor 8, respectively. The relevant version of the model SND-LD is considered for these experiments and the scenario-based results for each corridor are shown in Tables 4–6.

The results of the three considered instances are consistent with no apparent contradictions. As observed with the previous case study, rail transport continues not to receive freight flows in these experiments as well, except slightly for Corridor 2 with the modified

Table 3
Scenario analysis results of Instance 0.

Scenario	Modified parameter	Freight volumes on intermodal paths (%)	Freight volumes on all-road paths (%)	Modal split (% of tkm)		
				Road	Rail	IWW
Reference	None	36.59	63.41	78.07	0	21.93
Best-case	Road costs	36.62	63.38	78.17	0	21.83
	Rail costs	36.59	63.41	78.07	0	21.93
	IWW costs	46.05	53.95	70.74	0	29.26
	Road taxes	45.29	54.71	71.20	0	28.80
	Freight demands	39.63	60.37	76.23	0	23.77
	All	46.35	53.65	70.68	0	29.32
Worst-case	Road costs	41.52	58.48	74.10	0	25.90
	Rail costs	36.59	63.41	78.07	0	21.93
	IWW costs	32.92	67.08	80.84	0	19.16
	Road taxes	35.63	64.37	78.78	0	21.22
	Freight demands	36.80	63.20	77.85	0	22.15
	All	35.63	64.37	78.78	0	21.22
Middle-case	Road costs	36.59	63.41	78.07	0	21.93
	Rail costs	36.59	63.41	78.07	0	21.93
	IWW costs	36.59	63.41	78.07	0	21.93
	Road taxes	41.40	58.60	74.12	0	25.88
	Freight demands	37.90	62.10	77.04	0	22.96
	All	40.20	59.80	74.97	0	25.03

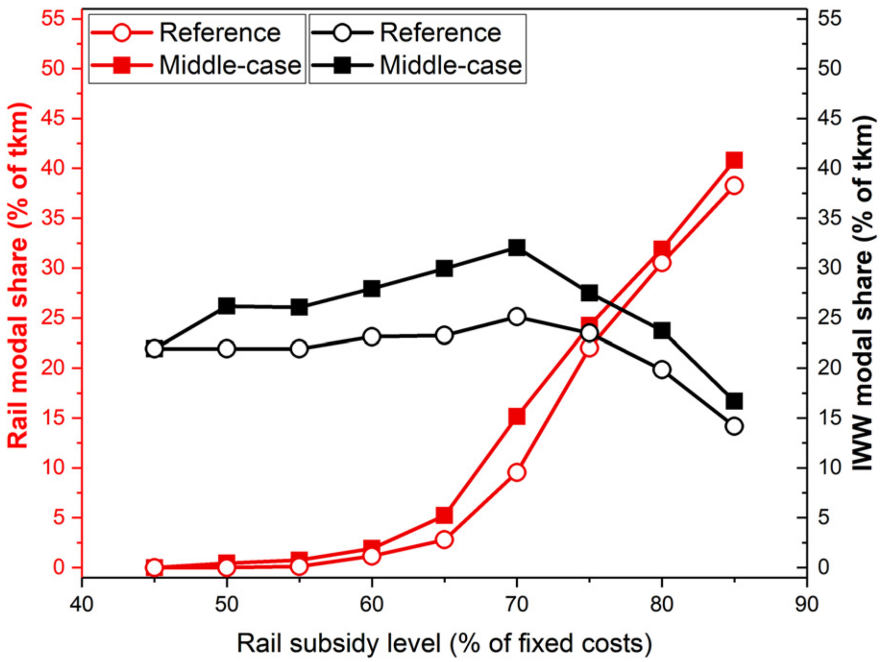


Fig. 1. Impact of the rail subsidies on the modal split in Instance 0.

scenario parameters. This further confirms the previously drawn conclusion about the indispensability of offering rail subsidies to sustain the services in comparison with the more affordable road services. Even though the results show that the IWW services are generally receiving less freight flows than in the previous case with shorter connections, considering the overall larger shipping demands at the

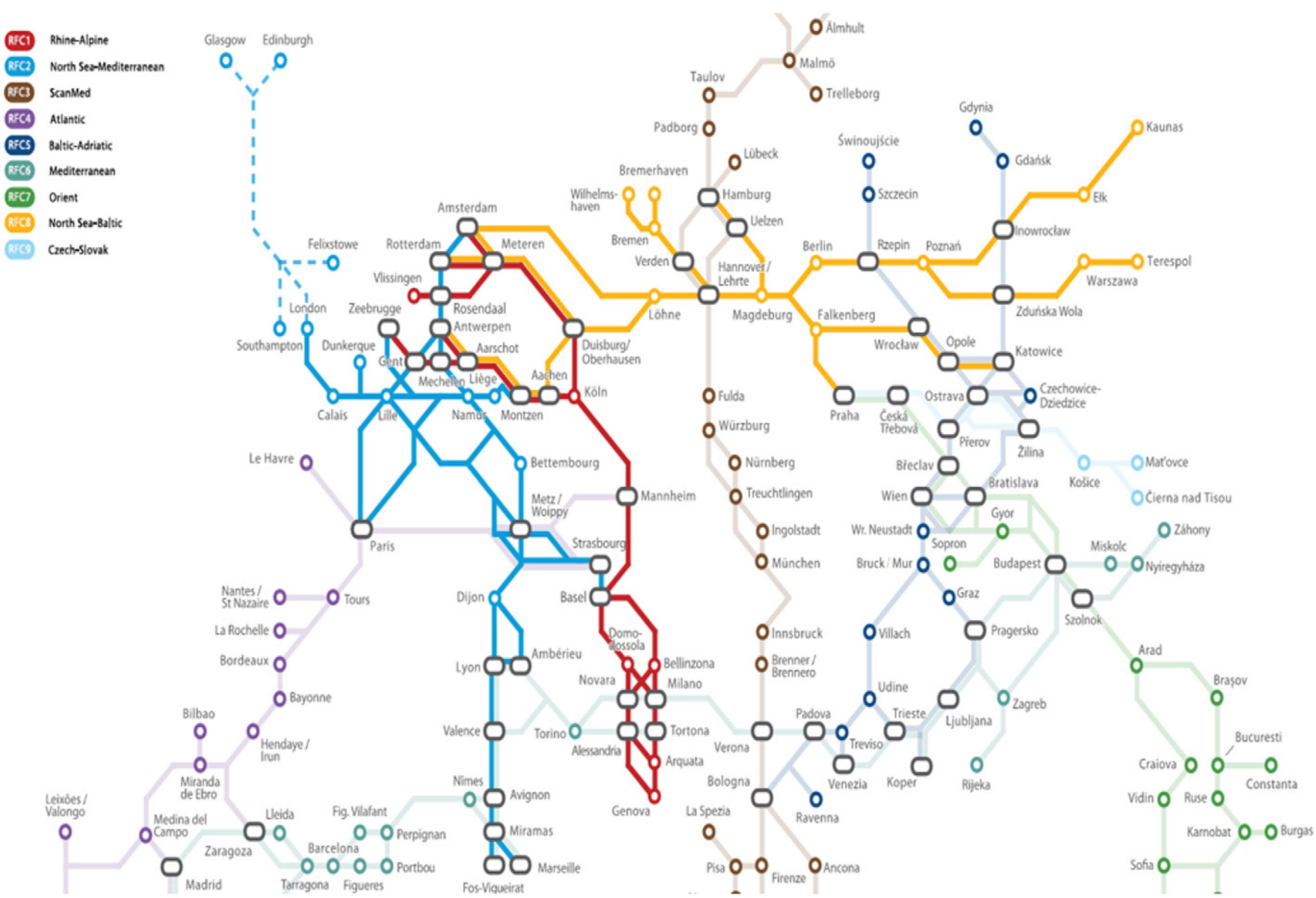


Fig. 2. Rail freight corridors in Europe (Corridor 1, 2 and 8).

Table 4
Scenario analysis results of Corridor 1.

Scenario	Modified parameter	Freight volumes on intermodal paths (%)	Freight volumes on all-road paths (%)	Modal split (% of tkm)		
				Road	Rail	IWW
Reference	None	6.55	93.45	96.01	0	3.99
Best-case	Road costs	5.13	94.87	97.10	0	2.90
	Rail costs	6.55	93.45	96.01	0	3.99
	IWW costs	6.49	93.51	96.00	0	4.00
	Road taxes	6.55	93.45	96.00	0	4.00
	Freight demands	5.94	94.06	96.74	0	3.26
	All	7.04	92.96	95.68	0	4.32
Worst-case	Road costs	6.55	93.45	96.00	0	4.00
	Rail costs	6.55	93.45	96.01	0	3.99
	IWW costs	5.12	94.88	97.10	0	2.90
	Road taxes	6.55	93.45	96.01	0	3.99
	Freight demands	5.68	94.32	96.72	0	3.28
	All	5.67	94.33	96.72	0	3.28
Middle-case	Road costs	6.55	93.45	96.01	0	3.99
	Rail costs	6.55	93.45	96.01	0	3.99
	IWW costs	6.55	93.45	96.01	0	3.99
	Road taxes	6.43	93.57	96.00	0	4.00
	Freight demands	6.29	93.71	96.23	0	3.77
	All	7.47	92.53	95.30	0	4.70

continental level, IWW are receiving considerable flows in terms of tkm. Nevertheless, their relatively now weaker position with respect to all-road transport could be attributed on one hand to the increased fixed costs of IWW services over longer distance, and on the other hand to the additional constraints regarding resource balancing by imposing a return service on each offered long haul service. The network structure may have also played a role in this observation. The difficulty to form long intermodal chains suggests the possibility that rail and IWW may not be adequately connected across Europe.

Similar to the previous remarks, road taxes have the greatest influence on diverting flows from road transport. Furthermore, the future evolution with respect to the middle-case scenario still brings an advantage to intermodal transport that is occasionally higher than the overall effect of the best-case scenario (i.e. Corridor 1 and 8). Another interesting observation, that also holds for the first case study, is that the modified road costs for the worst-case scenario have a positive effect on the intermodal market share. This could be interpreted by the fact that an (equal) increase in all modes' costs is assumed for the worst-case scenario. Therefore, when the road costs are individually increased, flows may be observed to divert to other modes, however this result does not hold when all the scenario parameters' modifications are jointly applied.

Now, the impact of rail subsidies on the modal split is tested at the continental level, as well as its variations between the scenarios and with respect to the drawn conclusions in the previous domestic case as shown in Fig. 3. Interestingly, the rail modal share exhibits a similar behaviour to that observed in the previous short-distance case, with respect to the threshold, after which offering rail subsidies becomes unjustifiable. An initial expectation would be to experience this threshold at an earlier stage, as freight transport over long distances offers, in principle, more consolidation and cost-saving opportunities to intermodal transport. However, this was not the case, which could potentially be explained by the data inaccuracies or the increase in rail fixed costs along with the increase in the covered corridors' distance. The IWW modal share exhibits, on the other hand, a non-uniform behaviour. While it mostly declines with high rail subsidies levels for Corridor 1, no obvious conclusion can be drawn from the changes it undergoes for Corridor 2 and 8. The underlying network structure could possibly be affecting these results; some intermodal itineraries could be composed of both rail and IWW services, so a

Table 5
Scenario analysis results of Corridor 2.

Scenario	Modified parameter	Freight volumes on intermodal paths (%)	Freight volumes on all-road paths (%)	Modal split (% of tkm)		
				Road	Rail	IWW
Reference	None	3.13	96.87	97.76	0	2.24
Best-case	Road costs	2.26	97.74	98.38	0	1.62
	Rail costs	3.13	96.87	97.76	0	2.24
	IWW costs	3.13	96.87	97.76	0	2.24
	Road taxes	3.78	96.22	97.35	0	2.65
	Freight demands	3.28	96.72	97.58	0	2.42
	All	4.82	95.18	96.63	0.67	2.70
Worst-case	Road costs	3.14	96.86	97.72	0	2.28
	Rail costs	3.13	96.87	97.76	0	2.24
	IWW costs	2.30	97.70	98.38	0	1.62
	Road taxes	3.13	96.87	97.76	0	2.24
	Freight demands	3.22	96.78	97.57	0	2.43
	All	2.54	97.46	98.19	0	1.81
Middle-case	Road costs	3.13	96.87	97.76	0	2.24
	Rail costs	3.13	96.87	97.76	0	2.24
	IWW costs	3.13	96.87	97.76	0	2.24
	Road taxes	2.28	97.72	98.38	0	1.62
	Freight demands	2.06	97.94	98.46	0	1.54
	All	3.87	96.13	97.21	0	2.79

Table 6
Scenario analysis results of Corridor 8.

Scenario	Modified parameter	Freight volumes on intermodal paths (%)	Freight volumes on all-road paths (%)	Modal split (% of tkm)		
				Road	Rail	IWW
Reference	None	1.49	98.51	99.18	0	0.82
Best-case	Road costs	1.49	98.51	99.18	0	0.82
	Rail costs	1.49	98.51	99.18	0	0.82
	IWW costs	2.67	97.33	98.17	0	1.83
	Road taxes	2.67	97.33	98.17	0	1.83
	Freight demands	2.38	97.62	98.42	0	1.58
	All	2.38	97.62	98.42	0	1.58
Worst-case	Road costs	2.67	97.33	98.17	0	1.83
	Rail costs	1.49	98.51	99.18	0	0.82
	IWW costs	1.49	98.51	99.18	0	0.82
	Road taxes	1.53	98.47	99.16	0	0.84
	Freight demands	1.53	98.47	99.16	0	0.84
	All	1.53	98.47	99.16	0	0.84
Middle-case	Road costs	1.49	98.51	99.18	0	0.82
	Rail costs	1.49	98.51	99.18	0	0.82
	IWW costs	1.49	98.51	99.18	0	0.82
	Road taxes	2.67	97.33	98.17	0	1.83
	Freight demands	1.43	98.57	99.21	0	0.79
	All	2.55	97.45	98.26	0	1.74

promotion of one mode could induce the other as well. However, at this point, no further evidence could confirm nor refute this hypothesis, apart from the observation that IWW modal share is, indeed, sensitive to the changes in rail subsidies.

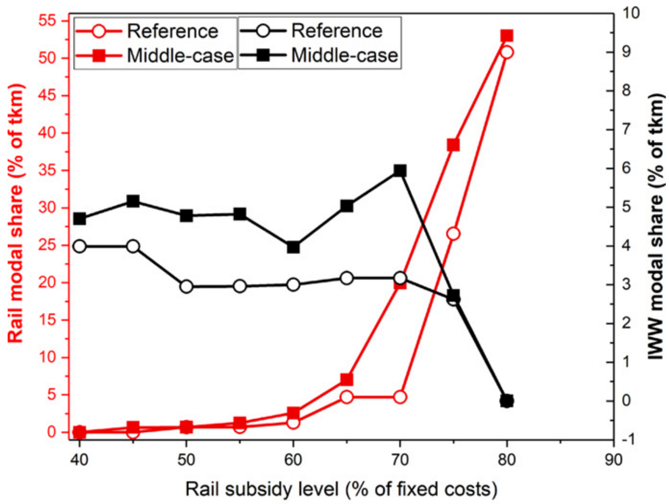
6. Impacts on GHG emissions and energy consumption

The environmental impacts of a transport system can be evaluated through the assessment of external costs or of the values of externalities. This assessment of transport external costs depends on parameters such as congestion, vehicle characteristics (e.g. Euro standards, speed, loading of a vehicle), meteorological condition, accidents, noise or air pollution. Forkenbrock (2001) compare external costs of rail and truck freight transport between cities in the United States. Quinet (2004) examines external transport cost estimates of European studies and demonstrates that the main disparities come from the specificity of the case under review and the type of cost calculated. Indeed, even more recently, most of research on external costs consists in applying the methodological valuation tools for determining their specific numerical values (Agarwal et al., 2015; Austin, 2015; Cravioto et al., 2013; De Langhe, 2017; Janic and Vleugel, 2012; Macharis et al., 2010; Maibach et al., 2008; Pérez-Martínez and Vassallo-Magro, 2013; Ricardo, 2014). However, the economic valuation of GHG emissions, for instance, vary up to six orders of magnitude (Nocera et al., 2015) due to uncertainties (Nocera et al., 2018). To the best of our knowledge, only Janic (2007, 2008) approximates generic external cost functions for rail and road transport. Yet, internalising external costs may encourage a shift towards intermodal transport (de Miranda Pinto et al., 2018; Macharis et al., 2010; Mostert et al., 2017, 2018; Santos et al., 2015; Zhang et al., 2015). Regarding the evaluation of the values of externalities, the Life Cycle Assessment methodology (LCA) is often used. The LCA methodology implies the analysis of the transport activity such as energy consumption and exhaust emissions, and of the processes connected with the electricity and fuel production, vehicles and infrastructure. LCA studies applied to inland freight transport generally focused on air emissions (Facanha and Horvath, 2007; Spielmann and Scholz, 2005; van Lier and Macharis, 2014). Merchan et al. (2019) provide values of externalities and external costs for inland freight transport on the Belgian case study. The functional unit chosen in their study, i.e. the reference unit to which the material and energy flows included in the life cycle processes are referenced, is “the tkm of freight transported in the different modes of inland freight transport”. Observing IWW transport, the main source of impact is the production of materials such as concrete and steel used in canals and port facilities. Besides, the authors show that road transport has the maximum impact, with rail freight transport presenting the minimum one.

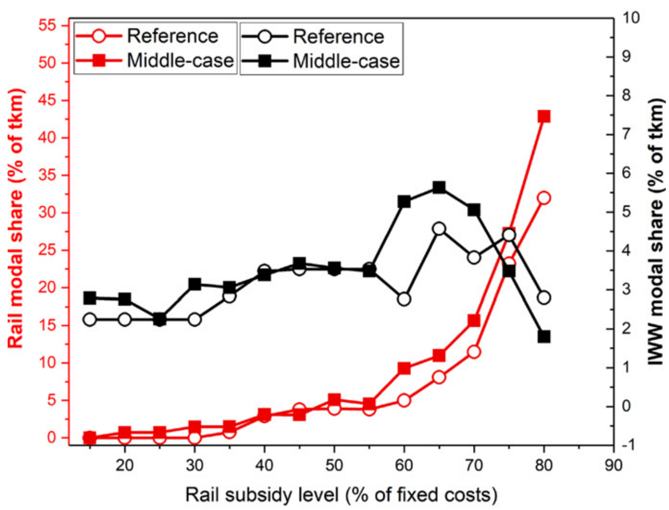
In Merchan et al. (2019), GHG emissions such as carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O) are converted into CO_2 equivalents (CO_2 eq.) so they can be compared. The LCA conducted by the authors provides the energy consumption and the CO_2 eq. for each inland freight transport modes in Belgium for the year 2012. A summary of their results are presented in Table 7.

Note that, thanks to the implementation of the “Euro” emission standards defined in a series of European Union directives, the air pollutant emissions from road transport have decreased. However, the barges fleet hasn’t changed in such a significant way because of the barges life span (approximately 40 years). However, the new regulation of the European Parliament and of the Council on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery (EUR-Lex, 2019) should reduce both the emission and energy consumption of IWW. In addition, as mentioned in Merchan et al. (2019), the results are valid for Belgium in 2012. The electricity supply mix, the degrees of electrification in rail transport or trucks, the emission engine technologies, the evolution of new engine technologies, and the resulting changes in vehicle fleet may bring new estimations.

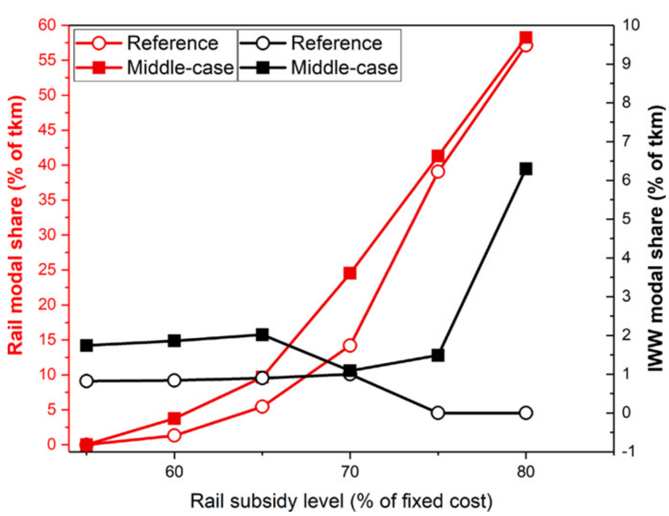
We apply the above methodology on the first case study, that is Belgium and its neighbours. Starting from the reference scenario, we compute the resulting emissions and energy consumption in each of the three other considered scenarios. Additionally, due to the high relevance of rail subsidies for intermodal transport, we include the results related to applying rail subsidies of 70% of the rail fixed costs: the threshold defined in Fig. 1 before an undesired modal shift could be observed from IWW to rail. Table 8 shows an increase of emissions and energy consumption for the best- and middle-case scenarios, and a decrease of the worst-case scenario. This is mainly due to the assumptions on freight demand. Rail subsidies allow to shift some flows to rail transport. The majority of the services used are from or to terminals/ports over distances by rail that are shorter than those by road. Indeed, in addition to the three rail freight corridors passing through Belgium, the country has one of the densest railway networks in the world, lying halfway between Paris and the industrial Ruhr



(a) Results of Corridor 1



(b) Results of Corridor 2



(c) Results of Corridor 8

Fig. 3. Impact of the rail subsidies on the modal split at the European freight corridors' level.

Table 7
Energy consumption and the CO_2 eq.
Source: Merchan et al. (2019).

	Road	Rail	IWW
Emission (kg CO_2 eq./tkm)	0.1130	0.0642	0.0747
Energy consumption (kJ/tkm)	994	457.551	288

area. Its freight transportation system heavily relies on the Port of Antwerp, the second largest container port in Europe. Belgium also has two smaller container ports, those of Zeebrugge and of Ghent and major hinterland terminals.

7. Conclusion

In the framework of addressing tactical planning aspects on consolidation-based transport networks and providing managerial insights into sustainable transport, this paper tackles service network design modelling within the intermodal transport context. As a mathematical framework, a path-based multicommodity formulation for service network design is developed, from the perspective of an intermodal transport operator. The decisions are two-fold: services' frequencies and itinerary-based routing of shipping demands, with a cost-minimization objective. The model is further developed for the long-distance case by defining the services by the dispatch day and adding resource-balancing constraints at the terminals.

Through a scenario-based analysis methodology, the impact of certain instrumental changes are being tested on the intermodal freight transport in order to draw meaningful insights about its potential future, at a time when it is facing strong competition from all-road transport. Two case studies have been conducted, both at the domestic and the continental level, regarding Belgium as a market point of interest. The following points summarize our main findings:

- From a costs' perspective, intermodal transport is more expensive than all-road transport, with a clear favouring of IWW over rail transport, potentially attributed to the high rail fixed costs. This observation holds at both the domestic and continental level.
- The increased road taxes have the greatest influence on diverting flows from road transport, followed by the increased freight demands as they create more opportunities for consolidation.
- By comparing the two sets of experiments, it is observed that intermodal transport receives less shares on longer corridors across Europe, contrary to the expectation that it could become more viable for larger cases. This finding can potentially be attributed to the additional resources balancing constraints that add a cost burden on the operators. Moreover, the studied case suggests that rail and IWW may not be adequately connected across Europe, in order to allow the formation of long intermodal chains.
- Generally speaking, both a future best- and middle-case scenario is moving towards intermodality's favour, however the expected modal shift is still far behind the one opted for by the European Commission.
- Rail subsidies are indeed necessary to make up for the high fixed costs. Experiments have shown that most cases share a certain recommended figure for the required subsidies, in order to reasonably increase the rail modal share, after which the modal split undergoes fast unnecessary changes. However, the changes in IWW modal shares should be monitored, given their sensitivity to the changes in rail subsidies, in order to avoid undesirable flow diversions.
- Finally, from an environmental perspective, our assessment shows an increase in emissions and energy consumption for the best- and middle-case scenarios in the Belgian case study.

Table 8
CO_2 equivalent emissions of Instance 0.

Scenario		Road	Rail	IWW	Total	Relative change
Reference	Mtkm	55.84	0	15.68	71.52	
	Emission (kt CO_2 eq.)	6.31	0	1.17	7.48	
	Energy consumption (TJ)	55.50	0	4.52	60.02	
Best-case	Mtkm	56.69	0	23.52	80.22	
	Emission (kt CO_2 eq.).	6.41	0	1.76	8.16	9.13%
	Energy consumption (TJ)	56.35	0	6.77	63.13	5.18%
Worst-case	Mtkm	50.11	0	13.5	63.61	
	Emission (kt CO_2 eq.).	5.66	0	1.01	6.67	−10.83%
	Energy consumption (TJ)	49.81	0	3.89	53.70	−10.53%
Middle-case	Mtkm	55.68	0	18.59	74.26	
	Emission (kt CO_2 eq.)	6.29	0	1.39	7.68	2.66%
	Energy consumption (TJ)	55.34	0	5.35	60.69	1.13%
Rail subsides (70%)	Mtkm	40.68	5.94	15.64	62.26	
	Emission (kt CO_2 eq.)	4.6	0.38	1.17	6.15	−17.83%
	Energy consumption (TJ)	40.44	2.72	4.50	47.64	−20.59%

This is chiefly attributed to the demands increase. Nevertheless, our results underline that in the presence of rail stimulating factors - such as subsidies - more efficient rail transport networks could be formed on the studied territory, resulting in a pronounced decrease in tkm and, consequently, in emissions and energy consumption.

As future perspectives, more accurate costs as well as updated freight demands data would certainly help draw conclusions that are better suited to the actual practices in intermodal transport nowadays.

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