Choice-driven Service Network Design and Pricing in Intermodal Transport

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Short summary

In intermodal transport, Service Network Design (SND) problems cover most tactical decisions of a carrier. Nevertheless, among the literature on SND, very few works include pricing decisions and the preferences of the shippers. In this study, we contribute to the existing body of knowledge by proposing a choice-driven and cycle-based formulation of the Service Network Design and Pricing (SNDP) problem which considers different aspects of the mode choice decisions of shippers. This formulation aims at finding the itineraries, frequencies and prices of the services that will maximize the profit of an intermodal carrier. Moreover, the mode choice preferences of shippers are modeled as a utility maximization accounting not only for the logistics costs, but also the frequency of the offered services and the accessibility of the transport mode. This bi-level formulation can be reformulated into a single level linear problem. The proposed model is compared to two other models (one cycled-based and one path-based) where shippers are assumed to be purely cost minimizers. While the latter generate higher profits, they also result in unrealistic mode shares, with road transport being negligible. On the other hand, the proposed formulation leads to mode shares that are considerably closer to reality. In addition, higher revenues can be generated with a cycle-based formulation compared to a path-based as it allows for more consolidation opportunities for the carrier.
Keywords: Choice-driven Optimization, Intermodal Transport, Mode Choice, Pricing, Service Network Design

1 Introduction

In intermodal freight transport, planning at the tactical level is of key importance to make the best use of existing infrastructure and available assets and to ensure reliable transport plans. In particular, Service Network Design (SND) problems cover, among other things, the decisions of transport operators about the itineraries to be served, the offered frequencies and how demand should be assigned to these services. The majority of existing studies on SND are formulated as a cost minimization of the transport operator and, therefore, do not include the revenues of fulfilling the transport orders, as highlighted by Elbert et al. (2020).

For the works actually applying a profit maximization, they mostly assume fixed tariffs that are included as parameters into the model, as in Bilegan et al. (2022). Only a handful of works include pricing as a decision of the problem. Some are using game theory paradigms to solve the SND, see for example Qiu et al. (2021), while others come up with a Mixed Integer Problem formulation, as for Martin et al. (2021).

In their work, Tawfik & Limbourg (2019) propose a bi-level SND and pricing model, with the upper level representing the profit maximization of an intermodal transport operator and the lower level being the costs minimization of shippers. The shippers can choose between the services proposed by the operator or a competition alternative. The latter is represented as direct trucking and a fixed cost is assumed for it. The authors then reformulate this bi-level model into a single-level problem and apply linearization procedures to come up with a Mixed Integer Linear Problem. Yet the representation of shippers here is limited as they look for the minimum cost and other attributes are not being evaluated.

The body of literature on choice-driven optimization has advanced in other domains such as assortment optimization, e.g., Davis et al. (2014), on-demand mobility solutions, e.g., Atasoy et al. (2015) and Sharif Azadeh et al. (2022) etc. Nevertheless, due the complexity of the decision-making process, it has not been yet sufficiently addressed in intermodal transport. The inputs from the demand side are typically considered as exogenous to the optimization problem or introduced with simplistic assumptions. In this paper, we represent the preferences of shippers more realistically rather than cost minimization and integrate this behavioral response within the service network design problem.

2 Methodology

In our study, we use the work by Tawfik & Limbourg (2019) as benchmark and expand it by introducing several new elements. Firstly, the path-based formulation is replaced by a cycle-based formulation. The latter is deemed more accurate to represent realistic decision-making. Indeed, most intermodal transport services go back and forth on an itinerary with a defined schedule. The cycle-based representation also enables a more elaborate representation of services as multiple intermediary stops can be added in both directions. In addition, it simplifies the asset management of the operators. In a path-based formulation, they may need to re-balance the vehicles at the end of the planning horizon; whereas a cycle-based representation ensures that each vehicle ends up at its starting point. It is noteworthy that we keep an arc-based pricing representation, as shippers will not be charged for a journey whose distance is longer than between the origin and the destination of their cargo.
Secondly, shippers' mode choice behavior is represented as the maximization of a utility function including not only logistics costs, but also non-monetary attributes. It is indeed known that there exist other influential factors, such as time and reliability, see for example Li et al. (2020). In our work, besides the price charged by the carrier, the utility function also consists of the offered frequency and the accessibility to the transport mode. The estimation of the model coefficients can be found in Nicolet et al. (2022). Compared to the benchmark formulation, where the frequency appeared only in the upper level, it now also appears in the lower level problem. In particular, it has a positive influence on the shippers' utility. Indeed, with the rise of just-in-time logistics and the observed trend of companies to reduce their inventories, it is desirable for shippers to have frequent transport services. We therefore develop a choice-driven and cycle-based service network design model (CD-SNDP) which is formulated next.

Mathematical formulation for the proposed CD-SNDP

The transport network is represented as a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ is the set of terminals and $\mathcal{A} = \{(i,j) : i,j \in \mathcal{N}, i \neq j\}$ the set of links between these terminals.

Upper level

The operator's fleet is heterogeneous and the different vehicle types are denoted by set $\mathcal{K}$. The number of available vehicles for type k is V_k and the corresponding capacity is Q_k.
Set $\mathcal{S}$ includes all the transport services that can be run by the operator. Unlike the benchmark, where each service corresponds to a single arc of $\mathcal{A}$, a service is composed of a sequence of arcs. Each arc in this sequence is called a leg and the whole sequence of legs for a given service s is noted $\mathcal{L}_s$. The cycle-based formulation of the problem implies that the sequence starts and ends at the same node.
The maximum number of cycles of service s that can be performed by vehicle type k is named W_{sk}: it typically consists of the maximum operating time divided by the cycle time (sum of travel time and time at terminals). Each service s has a fixed cost c_{sk}^{FIX} of operating it with vehicle type k and a variable cost c_{ijsk}^{VAR} per container transported between terminals i and j. Moreover, we introduce the parameter δ_{ijl_s}, which equals one if a container traveling from i to j uses the service leg l_s and zero otherwise.
The transport operator has three decision variables in the upper level problem:

- v_{sk} is the number of vehicles of type k that the operator allocates to each service s;
- f_{sk} is the frequency of service s per vessel type k;
- p_{ij} is the price per container charged to shippers wanting to transport goods from i to j.

Lower level

The shippers are represented as a whole: therefore, their demand is aggregated. The container transport demand between terminals i and j is denoted by D_{ij}. Shippers decide to assign demand to the transport operator or their competitors by the maximization of their utility. The utility function of using the services proposed by the transport operator between i and j is noted U_{ij} and is dependent on p_{ij} and f_{sk}, whereas the utility of using a competing alternative h is written U_{ij}^h. Finally, the decision variables of the lower level consist in the number of containers that are assigned to the operator's services (x_{ijsk}) and to every competing alternative (z_{ij}^h).
All the aforementioned sets, parameters and decision variables are listed in Table 1.

Table 1: Notation

Sets:	
$\mathcal{N}$	Terminals (indices: i, j)
$\mathcal{A}$	Arcs (i, j)
$\mathcal{K}$	Vehicle types (index: k)
$\mathcal{S}$	Potential services (index: s)
$\mathcal{L}_s$	Legs of service $s \in \mathcal{S}$ (index: l_s)
$\mathcal{H}$	Competing alternatives (index: h)
Parameters:	
V_k	Number of vehicles of type k in the operator's fleet
Q_k	Capacity of vehicle type k [TEUs]
W_{sk}	Maximum number of cycles of service s that can be performed by vehicle type k
c_{sk}^{FIX}	Fixed cost of operating service s with vehicle type k [€]
c_{ijsk}^{VAR}	Variable cost of transport between i and j with service s and vehicle type k [€/TEU]
δ_{ijl_s}	Dummy param. equal to 1 if container traveling from i to j uses service leg l_s, 0 otherwise
D_{ij}	Aggregated transport demand of shippers between i and j [TEUs]
U_{ij}	Utility of using the operator's services between i and j
U_{ij}^h	Utility of using competing alternative h between i and j
Variables:	
v_{sk}	Number of vehicles of type k assigned to service s by the operator
f_{sk}	Frequency of service s operated with vehicle type k
p_{ij}	Price charged by the operator to shippers wanting to transport goods from i to j [€/TEU]
x_{ijsk}	Cargo volume using service s operated with vehicle type k between i and j [TEUs]
z_{ij}^h	Cargo volume using competing alternative h between i and j [TEUs]

The proposed CD-SNDP is expressed as a bi-level Mixed Integer Problem as follows:

$$\max_{v,f,p,x,z} \quad \sum_{(i,j)\in\mathcal{A}} \sum_{s\in\mathcal{S}} \sum_{k\in\mathcal{K}} p_{ij} x_{ijsk} - \sum_{s\in\mathcal{S}} \sum_{k\in\mathcal{K}} c_{sk}^{\text{FIX}} f_{sk} - \sum_{(i,j)\in\mathcal{A}} \sum_{s\in\mathcal{S}} \sum_{k\in\mathcal{K}} c_{ijsk}^{\text{VAR}} x_{ijsk} \tag{1}$$

$$\text{s.t.} \quad \sum_{s\in\mathcal{S}} v_{sk} \leq V_k \qquad \forall k \in \mathcal{K} \tag{2}$$

$$f_{sk} \leq W_{sk} v_{sk} \qquad \forall s \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{3}$$

$$\sum_{(i,j)\in\mathcal{A}} \delta_{ijl_s} x_{ijsk} \leq Q_k f_{sk} \qquad \forall l_s \in \mathcal{L}_s,\ \forall s \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{4}$$

$$x_{ijsk} \leq \sum_{l_s\in\mathcal{L}_s} \delta_{ijl_s} D_{ij} \qquad \forall (i,j) \in \mathcal{A},\ \forall s \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{5}$$

$$p_{ij} \geq 0 \qquad \forall (i,j) \in \mathcal{A} \tag{6}$$

$$v_{sk} \in \mathbb{N} \qquad \forall s \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{7}$$

$$f_{sk} \in \mathbb{N} \qquad \forall s \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{8}$$

where x and z solve:

$$\max_{x,z} \quad \sum_{(i,j)\in\mathcal{A}} \left(\sum_{s\in\mathcal{S}} \sum_{k\in\mathcal{K}} U_{ij} x_{ijsk} + \sum_{h\in\mathcal{H}} U_{ij}^h z_{ij}^h \right) \tag{9}$$

$$\text{s.t.} \quad \sum_{s\in\mathcal{S}}\sum_{k\in\mathcal{K}} x_{ijsk} + \sum_{h\in\mathcal{H}} z_{ij}^h \;=\; D_{ij} \qquad \forall (i,j)\in\mathcal{A} \tag{10}$$

$$x_{ijsk} \geq 0 \qquad \forall (i,j)\in\mathcal{A},\ \forall s\in\mathcal{S},\ \forall k\in\mathcal{K} \tag{11}$$

$$z_{ij}^h \geq 0 \qquad \forall (i,j)\in\mathcal{A},\ \forall h\in\mathcal{H} \tag{12}$$

At the upper level, the objective function of the transport operator (1) is to maximize their profit. It is computed as the revenues from the transported containers minus the fixed and variable costs of the offered services. Constraint (2) is the fleet size constraint for each vehicle type. Constraint (3) ensures that the service's frequency is inferior to the maximum number of cycles that can be performed by the assigned vehicles. Constraint (4) assures that the total number of containers transported on each leg of every service does not exceed the available capacity of the service, whereas constraint (5) ensures that no container can be assigned to a service that does not go through the origin or destination terminal of the container. The domains of the operator's decision variables are defined by constraints (6)-(8).
Regarding the lower level, shippers seek to maximize their utility (9) by assigning their containers either to the operator's services or to the competition. Moreover, constraint (10) enforces the total transport demand to be met. Finally, constraints (11)-(12) define the domain of the decision variables of the shippers.
The presented model is transformed to a single level problem inspired by Tawfik & Limbourg (2019). In doing that, our formulation has multiple nonlinearities to deal with in order to reach a mixed integer linear program. These are due to the pricing decision as well as the utility function involving price and frequency which are both decision variables of the model. We make use of the strong duality theorem, the transformation of frequencies into binaries and the big M method in order to deal with the embedded nonlinearities.

3 Results and Discussion

To assess the performance of our method, it is applied to Inland Waterway Transport (IWT) of containers on a small network of three nodes (Rotterdam, Duisburg and Bonn) and compared with the results of the benchmark. We consider an IWT operator competing with two other modes (Road and Rail). The operator's fleet is homogeneous and composed of 30 vessels with a maximal capacity of 250 Twenty-Foot Equivalent Units (TEUs) and maximal operation time is assumed to be 120 hours per week. The sailing times and the time spent in ports as well as the costs for IWT and the two competing modes are estimated using the model of Shobayo et al. (2021); whereas the transport demand inputs come from the NOVIMOVE project, see Majoor et al. (2021).
Three different models are compared with each other:

- The Benchmark from Tawfik & Limbourg (2019) in which fleet constraints are added;
- The cycle-based version of the benchmark, SNDP, with Cost minimization of shippers, which is equivalent to the benchmark but with cycles allowed;
- The proposed Choice-Driven SNDP (CD-SNDP), with shippers' utility functions replacing costs.

Table 2 displays the main results of the three models applied to the three-node network. The cycle-based formulation offers more flexibility for the transport operator, who can propose services with intermediary stops and take advantage of consolidation opportunities, instead of offering only direct connections between two terminals. This translates into a 22% increase of the revenue with the SNDP compared to the benchmark. In the SNDP, almost all proposed services are between Rotterdam and Bonn with an intermediary stop in Duisburg; whereas this option is not available in the benchmark. As a result, the operator can serve higher shares of the demand between Rotterdam and Duisburg, where volumes are much greater than between Rotterdam and Bonn.
Nevertheless, both the benchmark and the SNDP rely on the assumption that shippers are only interested in minimizing the costs when choosing the transport mode. This results in unrealistic modal shares, where only a tiny fraction of the total demand is assigned to Road. When the cost minimization is replaced by the utility maximization to get the CD-SNDP, the modal shares become much closer to the reality. Indeed, the data collected in Majoor et al. (2021) shows that the shares of container transport between the three considered terminals are 43% for IWT, 48% for Road and 8% for Rail. The integration of utility in the model implies that not all flows can be served by the operator. In particular, no demand is served between Duisburg and Bonn because

Table 2: Results on a 3-nodes network, with served demand without parentheses for import flows → and in parentheses for export (←).

		Benchmark	SNDP	CD - SNDP
	Total revenue [mio €]	3.43	4.17	2.03
Weekly service frequencies	RTM ↔ DUI	15	0	0
	RTM ↔ BON	6	4	0
	DUI ↔ BON	27	0	0
	RTM ↔ DUI ↔ BON	-	26	30
Served demand by IWT	RTM ↔ DUI	58% (45%)	100% (77%)	100% (89%)
	RTM ↔ BON	79% (100%)	53% (67%)	53% (0%)
	DUI ↔ BON	100% (100%)	97% (100%)	0% (0%)
Modal shares	IWT	75%	89%	48%
	Road	0%	1%	50%
	Rail	25%	10%	3%

IWT is not competitive enough compared to Road. Undoubtedly, the revenue is lower in the CD-SNDP compared to the two other formulations. Yet it embeds a more realistic response of the demand to the decisions of the IWT operator. Moreover, it still emphasizes the benefits of our cycle-based formulation as the optimal solution includes no direct links at all, but only cycle services that stop at every terminal.

4 Conclusions

The results support that including a more detailed modeling of the mode choice behavior of shippers allows our service network design model to more accurately represent the situation. Moreover, the benefits of a cycle-based formulation in terms of flexibility and profitability are highlighted. The analysis needs to be carried out for bigger transportation networks in order to see the potential of the proposed methodology. Furthermore, our immediate future research relates to the inclusion of shippers' heterogeneity in the mode choice behavior for further improving the representation of the real situation. When the decision-making process of both the transport operators and shippers are represented more realistically, the transport systems as such can be improved further towards sustainability goals as the resources can be allocated to the right entities at the right time and place.

Acknowledgements

This research is supported by the project "Novel inland waterway transport concepts for moving freight effectively (NOVIMOVE)". This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 858508.

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