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Synchromodal transport planning considering heterogeneous and vague preferences of shippers ☆

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ABSTRACT

In synchromodal transport, a freight forwarder usually serves multiple shippers with heterogeneous and vague preferences, such as low-cost, fast, or reliable transport. Ignoring shippers' preferences will negatively impact the satisfaction of shippers and lead to the loss of them in the longer run. In order to incorporate these preferences, a Synchromodal Transport Planning Problem with Heterogeneous and Vague Preferences (STPP-HVP) is proposed and formulated as a mathematical model. Heterogeneous and Vague Preferences (HVP) are modeled through Multiple Attribute Decision Making approaches that integrate fuzzy set theory. The proposed model has two objectives, i.e., maximizing the number of served requests and minimizing the transportation cost. Preferences of shippers are set as constraints such that the freight forwarder needs to satisfy the preferred levels for each attribute. A heuristic algorithm (Adaptive Large Neighborhood Search) is proposed to find (near) optimal solutions. The case study in the European Rhine–Alpine corridor demonstrates that the proposed model can provide more attractive solutions to shippers compared with optimization which ignores preferences. Under various scenarios, the attributes, such as cost, time, emissions, reliability, and risk of damage, are analyzed and the (near) optimal modes and routes are suggested according to HVP. Moreover, the results show that the conflicts among attributes, conflicts among shippers, and conflicts between the freight forwarder and shippers are resolved by making one actor more satisfied without compromising any other actor's preferences.

1. Introduction

Through the coordination and cooperation of stakeholders and the synchronization of operations, intermodal transport is transforming into synchromodal transport to provide more efficient, reliable, flexible, and sustainable services (Giusti et al., 2019). Synchromodal transport is the latest generation of a family of transport systems designed to improve the overall efficiency of the transport system and provide demand-driven transport services by combining several transport modes (Tavasszy et al., 2017; Khakdaman et al., 2020). Synchromodal transport involves different stakeholders, including shippers, freight forwarders, and carriers, and the relationship of them is illustrated in Fig. 1. A shipper is the entity that is responsible for starting the movement

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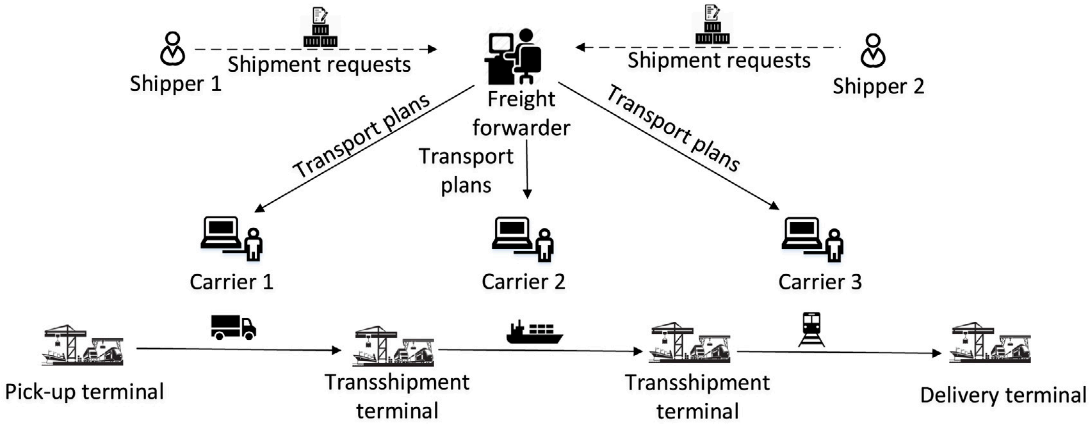


Fig. 1. The relationships between shippers, carriers, and the freight forwarder in synchromodal transport.

of cargo and makes the decision on the total freight price. The freight forwarder organizes shipments for shippers to transport containers from origin to destination and usually plays a role between shippers and carriers. A carrier is the entity that actually transports cargo. This study proposes an optimization model for the freight forwarder. In cases where shippers work directly with carriers without a freight forwarder, the user of our proposed model could also be the carrier. In practice, the freight forwarder could be the third-party logistics provider, transport operator, or transport platform, and we refer to them collectively as "freight forwarder" in this study.

Considering preferences of shippers become more important in the context of synchromodal transport due to the modal-free booking nature. In synchromodal transport, transport plans can change dynamically to better match actual transport demand (Tavasszy et al., 2017; Delbart et al., 2021). It is therefore hard (and undesirable) for shippers to make mode choice and routing decisions. According to a large survey among global shippers (Khakdaman et al., 2020), two-thirds of shippers in synchromodal transport are willing to cede modal control to freight forwarders. In other words, shippers in synchromodal transport accept a mode-free booking and only determine the price and quality requirements (Behdani et al., 2014). Freight forwarders with network-wide freedom can then fully utilize their authority on mode and route control to maximize the overall performance. However, it does not mean that freight forwarders will neglect requirements and preferences of shippers. One aim of the synchromodal transport is to provide demand-driven transport services by combining several transport modes (Tavasszy et al., 2017; Khakdaman et al., 2020), while considering shippers' preferences can match services and demands in a better way and improve the service level by utilizing advantages of different modes.

Over time, with the competition in product and service markets, shippers became concerned about service attributes such as cost, time, reliability, risk of damage, and sustainability (Kurtuluş and Çetin, 2020). A freight forwarder works with multiple shippers with heterogeneous preferences due to their characteristics, such as product type, company size, the firm location, etc. The most appropriate transport plan needs to be adopted based on a full understanding of the taste heterogeneity of service requirements from shippers. The term "taste heterogeneity" reflects that the shippers take different attributes into account or value the same attributes differently (Arunotayanun and Polak, 2011). A full understanding of preferences will not only reduce unnecessary costs, but also improve the service level by the provision of customized services. However, understanding preferences is not easy because the preference information provided by shippers is usually subjective and vague due to the shippers' limited attention, time pressure, and lack of data. A rational approach towards decision-making should take into account human subjectivity, e.g., using fuzzy set theory to handle the vagueness of preferences (Chen and Hwang, 1992). Furthermore, the freight forwarder also needs to resolve conflicts between the freight forwarder's objectives and shippers' preferences. Although much progress has been made on how to generate synchromodal services in a more efficient manner, less research focuses on how to better understand shippers' preferences and make the transport plan based on the preferences (SteadieSeifi et al., 2014; Giusti et al., 2019).

In a word, shippers' heterogeneous and vague preferences pose difficulties in setting up an appropriate transportation solution for freight forwarders in synchromodal transport. To improve the service level of freight forwarders and the satisfaction of shippers, this research establishes an optimization model. The focus of this research is to make synchromodal transport plans considering heterogeneous and vague preferences of shippers. The proposed model includes two parts: (a) synchromodal transport planning and (b) preference modeling. In part (a), a mathematical model is formulated for the synchromodal transport planning problem. In part (b), a Multiple Attribute Decision Making (MADM) model is developed based on fuzzy set theory to handle the heterogeneous and vague preferences. According to the preferences and actual values of attributes, the satisfaction of shippers is calculated. Part (a) incorporates part (b) by setting satisfaction as constraints, therefore the transport plans generated by part (a) are in line with shippers' preferences in part (b). Moreover, a heuristic algorithm, i.e., Adaptive Large Neighborhood Search (ALNS), is proposed to reduce the computation time.

The main contributions of this paper are summarized as follows: (a) we develop a mathematical model for synchromodal transport planning and introduce the MADM integrating fuzzy set theory to capture heterogeneous and vague preferences; (b) we propose the

Table 1
Comparison between the proposed model and existing models in the literature.

Article	Field	Level	Problem	Heterogeneity	Vagueness	Preferences of whom	Preferences on what
Road transport (parcel delivery)							
Zhang et al. (2013)	Road	Operational	SVRPSTW	✓		Recipient	On-time shipment delivery
Ghannadpour et al. (2014)	Road	Operational	DVRPFTW		✓	Recipient	Time window
Afshar-Bakeshloo et al. (2016)	Road	Operational	S-GVRP		✓	Recipient	Time window
Los et al. (2018)	Road	Operational	GPDPTWP			Recipient	Delivery location
Baniamerian et al. (2018)	Road	Operational	VRPCDTWS			Recipient	Time window
Dumez et al. (2021)	Road	Operational	VRPDO			Recipient	Delivery location
Maritime, railway, or intermodal/synchromodal transport							
Duan et al. (2019)	Railway	Tactical	SNDP	✓		Shipper	Time and Reliability
Zhang et al. (2020b)	Intermodal	Tactical	SNDP	✓		Shipper	Cost, Time, Emission, Reliability, Frequency, Safety, Flexibility, and Traceability
Jiang et al. (2020)	Maritime	Tactical	LSSD			Freight forwarder and shipper	Ship arrival time
Cheng and Wang (2021)	Maritime	Tactical	CLSNDP			Shipper	Freight rate, Cost, and Time
Shao et al. (2022)	Intermodal	Operational	IFRP	✓		Shipper	Cost, Timeliness, Reliability, and Flexibility
Our paper	Synchromodal	Operational	STPP-HVP	✓	✓	Shipper	Cost, Time, Reliability, Risk of damage, and Emissions

SVRPSTW: Stochastic Vehicle Routing Problem with Soft Time Window constraints; DVRPFTW: Dynamic Vehicle Routing Problem with Fuzzy Time Windows; S-GVRP: Satisfactory-Green Vehicle Routing Problem; GPDPTWP: Generalized Pickup and Delivery Problem with Time Windows and Preferences; VRPCDTWS: Vehicle Routing Problem with Cross-Docking and Time Windows considering customer Satisfaction; VRPDO: Vehicle Routing Problem with Delivery Options; SNDP: Service Network Design Problem; LSSD: Liner Shipping Schedule Design; CLSNDP: Container Liner Shipping Network Design Problem; IFRP: Intermodal Freight Routing Problem; STPP-HVP: Synchromodal Transport Planning Problem with Heterogeneous and Vague Preferences.

ALNS algorithm to reduce the computation time; (c) we apply the proposed model to different scenarios using real-world data. In the case study, we compare results without preferences, with homogeneous preferences, and with heterogeneous preferences. Five attributes, i.e., cost, time, reliability, risk, and emissions, are considered. The attribute values, mode shares, and satisfaction values are also compared in these scenarios. Moreover, the performance of the ALNS is evaluated and results of re-planning are analyzed.

The remainder of this paper is organized as follows: Section 2 presents a brief literature review. Section 3 describes the studied problem by illustrating two sub-problems, i.e., (a) how to make synchromodal transport plans and (b) how to model preferences. In Section 4, we first present the mathematical model for sub-problem (a) in Section 4.1 and Section 4.2 provides the MADM approaches for sub-problem (b). Section 5 proposes a customized ALNS. In Section 6, experimental settings and results are provided, and the ability of the model to handle multiple attributes and different actors is evaluated. Section 7 concludes and gives future research directions.

2. Literature review

Based on the decision horizon of the planning problems, synchromodal transport planning can be divided into strategic, tactical, and operational planning (SteadieSeifi et al., 2014). Strategic, tactical, and operational planning problems related to investment decisions, service network design, and matching services and requests, respectively. Uncertainty, cooperation, and dynamic optimization at different levels have been well studied, while the number of studies that research optimization considering preferences in synchromodal transport is still limited (SteadieSeifi et al., 2014; Delbart et al., 2021). To the best of our knowledge, there is no study considering shippers' preferences at the operational level in the context of synchromodal transport planning.

Table 1 compares our paper and the relevant studies in the literature. In road transport, such as package delivery, preferences of customers are considered at the operational level. Los et al. (2018), Dumez et al. (2021) consider the delivery location preferences by providing multiple options. Los et al. (2018) minimize the sum of costs and dissatisfaction values and Dumez et al. (2021) set the satisfaction of preference levels as constraints. Ghannadpour et al. (2014), Afshar-Bakeshloo et al. (2016) and Baniamerian et al. (2018) take the fuzzy or soft time window preferences of customers into account and consider the satisfaction of customers in the objective. Zhang et al. (2013) use customer service level constraints to ensure the on-time shipment delivery preferences of customers.

Compared with customers in road transport who are recipients and focus on the delivery location or time, shippers in maritime, railway, or intermodal/synchromodal transport care more about the performance of the whole itinerary, such as cost, time, reliability, etc. Cheng and Wang (2021) address the container liner shipping network design and take shippers' preferences on freight rate, cost, and time into account. Jiang et al. (2020) consider preferences on the weekly ship arrival times of big customers (freight forwarders and shippers) in near-sea container shipping. Duan et al. (2019) solve a railway service network design problem with heterogeneous preferences for transport time and reliability, and the Value of Time (VOT) and Value of Reliability (VOR) are taken into account in the objective. Zhang et al. (2020b) optimize the China Railway express network and homogeneous and heterogeneous preferences of shippers are considered. Their results show that the sustainability and service level of the network is improved by recognizing the heterogeneous preferences of shippers. Duan et al. (2019) and Zhang et al. (2020b) consider heterogeneous preferences, which is similar to our paper. However, there are three main differences between this study and their studies: (a) Duan et al. (2019) and Zhang et al. (2020b) solve the service network design problem at the tactical level and the routing optimization model in this paper is at the operational level; (b) Duan et al. (2019) and Zhang et al. (2020b) do not consider vague preferences, while our study proposes approaches to model them; (c) although Zhang et al. (2020b) consider road transport, Duan et al. (2019) and Zhang et al. (2020b) focus on rail transport, and this paper studies synchromodal transport with three modes (waterway, railway, and road). Shao et al. (2022) also consider preferences at the operational level. The context of their study is intermodal transport, while our paper is in the context of synchromodal transport. Shippers express preferences in different ways in intermodal and synchromodal transport. The shippers in Shao et al. (2022) express their preferences during the optimization by accepting or rejecting solutions. However, in synchromodal transport, shippers cede modal control to the freight forwarder, which allows flexible selection and real-time switching of modalities for the freight forwarder. Therefore, it is a mode-free booking and shippers usually express vague preferences to the freight forwarder in synchromodal transport. Our study uses fuzzy set theory to capture vague preferences of shippers, which is not considered in their study. In addition, the maximum number of requests in their case study is five, while our study considers instances with 100 requests.

In the decision-making domain, preferences are often considered in Multiple Criteria Decision Making (MCDM), which can be divided into Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM) (Kahraman, 2008). The MADM is associated with problems where alternatives have been predetermined and the decision-maker is to select/prioritize/rank a finite number of courses of action. On the other hand, in MODM the alternatives have not been predetermined and the decision maker's primary concern is to design the "most" promising alternative with respect to limited resources (Chen and Hwang, 1992). In the synchromodal transport, most studies build MODM models considering the freight forwarder/carrier's preferences rather than shippers' preferences (Baykasoğlu and Subulan, 2016; Zhang et al., 2020a, 2022a). The decision-making process considering shippers' preferences belongs to MADM because the freight forwarder needs to evaluate predetermined alternatives provided by the optimization model. Therefore, this study is a combination of routing optimization and MADM.

3. Problem description

The main research problem of this study is Synchromodal Transport Planning Problem with Heterogeneous and Vague Preferences (STPP-HVP) for the freight forwarder. The STPP-HVP is an optimization problem for synchromodal transport considering time windows, capacity, multiple modes, transshipments, and preferences. As shown in Fig. 2, the STPP-HVP consists of two sub-problems:

1. How to optimize the synchromodal transport operations for the freight forwarder, i.e., solve the Synchromodal Transport Planning Problem (STPP)?
2. How to model the Heterogeneous and Vague Preferences (HVP) of shippers?

In this study, the STPP is formulated as a mathematical model and HVP is modeled by the MADM integrating fuzzy set theory. To reduce the computation time, the STPP-HVP is solved by a customized ALNS. For each shipper, a number of alternatives could be obtained by the ALNS. The satisfaction values of alternatives are calculated by the MADM integrating fuzzy set theory according to shippers' preferences. Alternatives with low satisfaction will be filtered and rejected by the ALNS. The chosen alternatives will constitute the overall transport plan.

The following sub-sections illustrate these two sub-problems in detail.

3.1. Synchromodal transport planning problem (STPP)

The transport network with multiple modes $w \in W$ is defined as a directed graph $G = (N, A)$, where N represents the set of terminals (ports and train/truck stations) and $A = \{(i,j)|i,j \in N, i \neq j\}$ represents the set of arcs (roads, railways, and inland waterways). Barges and trains have fixed capacities and we assume that a truck service is a truck fleet with an unlimited number of trucks. Shipment requests are sent by shippers to the freight forwarder. Each request $r \in R$ is characterized by its pickup terminal $p(r)$ and time window $[a_{p(r)}, b_{p(r)}]$, delivery terminal $d(r)$ and time window $[a_{d(r)}, b_{d(r)}]$, number of containers q_r, and preferences. A solution of the STPP is a set of $|K|$ routes and route of vehicle k starts at depot $o(k)$ and ends at depot $o'(k)$. The depot $o(k)/o'(k) \in O$ belongs to the set of terminals N. At any moment, the number of containers carried simultaneously by vehicle k cannot exceed capacity u_k. Containers have to be picked up in the designated terminal and can be carried by more than one vehicle/mode to the destination. The shift between two vehicles/modes is achieved at specific terminals, which are called transshipment terminals ($T \subseteq N$). Fig. 3 gives an example of such an STPP problem. Requests 1 and 2 of shippers 1 and 2 are transported by two and three vehicles, respectively. Besides transports with transshipments, using only one vehicle to transport containers from origination to destination is also possible.

3.2. Heterogeneous and vague preferences (HVP)

The solution in Section 3.1 also needs to respect preferences of shippers. For example, in Fig. 3, the solution is only accepted by the freight forwarder if the preferences of both shippers are respected after satisfaction calculation. In synchromodal transport, the preferences of shippers are usually expressed linguistically and vaguely. For example, the importance level of attribute 1 is "very high", while attribute 2 has a "low" level of importance. Assume that there are n shippers served by the freight forwarder and that

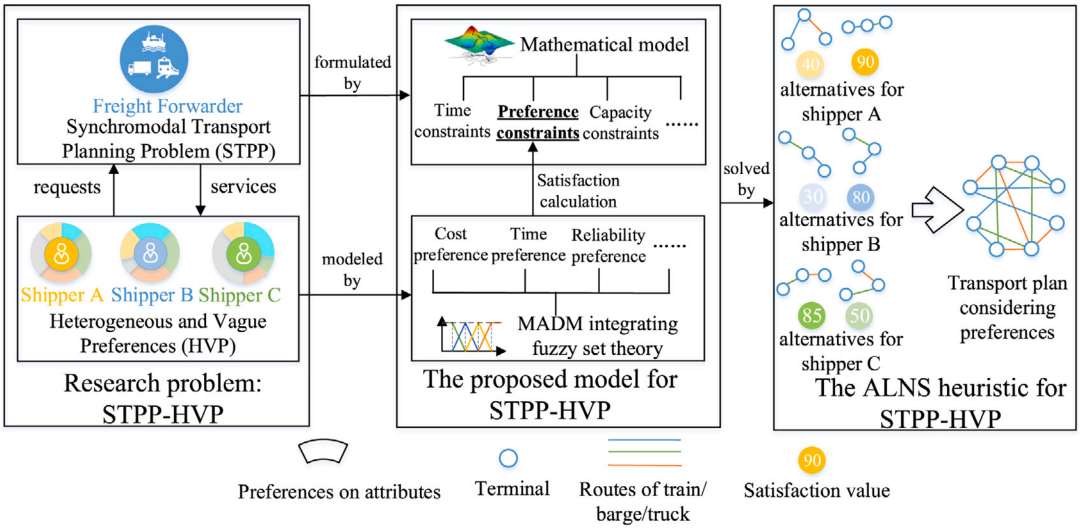


Fig. 2. The research problem and proposed methodology.

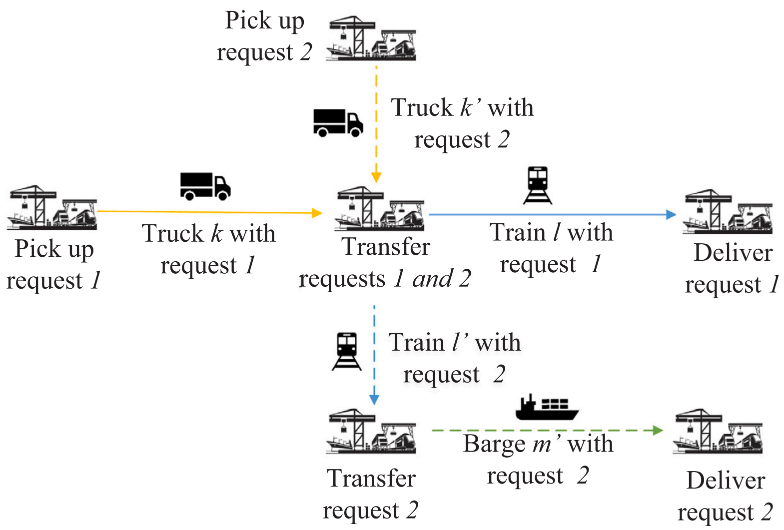


Fig. 3. An example of the STPP-HVP.

there are m attributes that characterize the services provided by the freight forwarder. Each shipper r expresses vague preferences $\tilde{w}_i^r$ towards attribute i. The value of attribute i for shipper r is f_i^r. Whether preference $\tilde{w}_i^r$ is satisfied or not is judged according to the value f_i^r. Take the cost attribute as an example, if $\tilde{w}_i^r$ is level 2, which means the shipper thinks the cost is important, and f_i^r is 0.3, which means the unit cost is 0.3 euro/km/TEU and is very low, then the shipper will be satisfied with a high probability. The attribute values and heterogeneous preferences are represented by the following matrices:

$$\begin{bmatrix} f_1^1 & f_2^1 & \cdots & f_m^1 \\ \tilde{w}_1^1 & \tilde{w}_2^1 & \cdots & \tilde{w}_m^1 \end{bmatrix} \begin{bmatrix} f_1^2 & f_2^2 & \cdots & f_m^2 \\ \tilde{w}_1^2 & \tilde{w}_2^2 & \cdots & \tilde{w}_m^2 \end{bmatrix} \cdots \begin{bmatrix} f_1^n & f_2^n & \cdots & f_m^n \\ \tilde{w}_1^n & \tilde{w}_2^n & \cdots & \tilde{w}_m^n \end{bmatrix}$$

Vague preferences are linguistic terms provided by shippers, such as “I would like to transport cargoes timely” or “I think the transport time is important”, and quantifying the vague preferences is the first challenge for the freight forwarder. Shipper’s satisfaction towards an alternative for a request r need to be calculated. When the satisfaction is less than a predefined satisfaction benchmark, this alternative will not be chosen. Another challenge is satisfying heterogeneous preferences on multiple attributes of shippers as well as the freight forwarder itself. The term “attributes” may be referred to as “goals” or “criteria”, which could be cost, time, reliability, etc. Among attributes, there may be conflicts because of the inherent interdependence, e.g., reducing transport time usually means choosing an expensive mode. Conflicts also exist among shippers because the resources owned by the freight forwarder are limited. Considering shippers’ preferences, e.g., low-risk transport, may increase the transport cost of the freight forwarder. Therefore, there are also conflicts between the freight forwarder and shippers. An appropriate approach needs to be developed to solve these conflicts.

4. The proposed model for the STPP-HVP

To optimize the transport plan considering preferences, the STPP is formulated as a mixed integer programming problem and HVP is modeled by the MADM integrating fuzzy set theory.

4.1. The mathematical model for the STPP-HVP

The notation used for formulating the problem is presented in Table 2. There are two objectives. One objective (F_1) is to maximize the number of served requests, and another objective (F_2) is minimizing cost, which consists of transport cost, transfer cost, storage cost, carbon tax, waiting cost, and delay penalty (Guo et al., 2020). The emissions are calculated using an activity-based method by Demir et al. (2016) and the amount of emissions is related to vehicle type, distance, and amount of containers. The model will choose the solution with a higher objective value of F_1, and the solution with a lower objective value of F_2 will be chosen if objective values of F_1 are the same. In this way, the model will try to serve as many as requests in the first place and choose the solution with minimum costs thereafter.

Objective:

$$\max \ F_1 = \sum_{r\in R}\sum_{k\in K}\sum_{j\in N} y^{kr}_{p(r)j} \tag{1}$$

$$\begin{aligned}\min \ F_2 = &\sum_{k\in K}\sum_{(i,j)\in A}\sum_{r\in R}(c^1_k\tau^k_{ij} + c^{1'}_k d^k_{ij})q_r y^{kr}_{ij} + \sum_{k,l\in K,k\neq l}\sum_{r\in R}\sum_{i\in T}(c^2_k + c^2_l)q_r s^{kl}_{ir}\\
&+ \sum_{k\in K}\sum_{(i,j)\in A_p}\sum_{r\in R} c^2_k q_r y^{kr}_{ij} + \sum_{k\in K}\sum_{(i,j)\in A_d}\sum_{r\in R} c^2_k q_r y^{kr}_{ij} + \sum_{k,l\in K,k\neq l}\sum_{r\in R}\sum_{i\in T} c^3_k q_r s^{kl}_{ir}(t'^{lr}_i - \bar{t}^{kr}_i)\\
&+ \sum_{k\in K}\sum_{(i,j)\in A_p}\sum_{r\in R} c^3_k q_r y^{kr}_{ij}(t'^{kr}_i - a_{p(r)}) + \sum_{k\in K}\sum_{(i,j)\in A}\sum_{r\in R} c^4_k e_k q_r d^k_{ij} y^{kr}_{ij}\\
&+ \sum_{k\in K_{\text{b\&t}}}\sum_{i\in N} c^5_k t^{\text{wait}}_{ki} + \sum_{r\in R} c^{\text{delay}}_r q_r t^{\text{delay}}_r\end{aligned} \tag{2}$$

Constraints (3)–(21) are the spatial constraints. Constraints (3) enforce that each vehicle may initiate at most one route from its beginning depot; Constraints (4) ensure that the same vehicle ends the route at its end depot. Not all of the available vehicles may have to be used in synchromodal transport, therefore we use "$\leqslant 1$" instead of "$= 1$" in constraints (3). Objective function (1) ensures that as many requests as possible are served, and x^k_{ij} equals to 1 when vehicle k serves requests on arc ij. When a vehicle is used, it is forced to start from the beginning depot by Constraints (7), which maintain flow conservation of the vehicles through the nodes in the network. Constraints (5) and (6) ensure that containers for each request must be picked and delivered at its pickup and delivery terminal, respectively.

$$\sum_{j\in N} x^k_{\overline{o}(k)j} \leqslant 1 \quad \forall k \in K_{\text{b\&t}} \tag{3}$$

$$\sum_{j\in N} x^k_{\overline{o}(k)j} = \sum_{j\in N} x^k_{j\overline{o'}(k)} \quad \forall k \in K_{\text{b\&t}} \tag{4}$$

$$\sum_{k\in K}\sum_{j\in N} y^{kr}_{p(r)j} \leqslant 1 \quad \forall r \in R \tag{5}$$

$$\sum_{k\in K}\sum_{j\in N} y^{kr}_{jd(r)} \leqslant 1 \quad \forall r \in R \tag{6}$$

Constraints (7) and (8)–(11) represent flow conservation for vehicle and request flows, respectively. Constraints (8) and (9) are for regular and transshipment terminals, respectively. If request r is not transferred at terminal $i \in T$ but vehicle k passes terminal i due to operations for other requests, Constraints (8) do not work on request r. Therefore, additional flow conservation of requests (Constraints (10) and (11)) are added. Constraints (12) link y^{kr}_{ij} and x^k_{ij} variables in order to guarantee that for a request to be transported by a vehicle, that vehicle needs to traverse the associated arc.

$$\sum_{j\in N} x^k_{ij} - \sum_{j\in N} x^k_{ji} = 0 \quad \forall k \in K_{\text{b\&t}},\ \forall i \in N \setminus \overline{o}(k), \overline{o'}(k) \tag{7}$$

$$\sum_{j\in N} y^{kr}_{ij} - \sum_{j\in N} y^{kr}_{ji} = 0 \quad \forall k \in K,\ \forall r \in R,\ \forall i \in N \setminus T, p(r), d(r) \tag{8}$$

$$\sum_{k\in K}\sum_{j\in N} y^{kr}_{ij} - \sum_{k\in K}\sum_{j\in N} y^{kr}_{ji} = 0 \quad \forall r \in R,\ \forall i \in T \setminus p(r), d(r) \tag{9}$$

$$\sum_{j\in N} y^{kr}_{ij} - \sum_{j\in N} y^{kr}_{ji} \leqslant \sum_{l\in K} s^{lk}_{ir} \quad \forall k \in K,\ \forall r \in R,\ \forall i \in T \setminus p(r), d(r) \tag{10}$$

Table 2
Notation.

Sets:	
W	Set of modes indexed by w.
R	Set of requests indexed by r.
N	Set of terminals indexed by i and j. $O/\overline{O} \subseteq N$, set of depots/virtual depots. $P/D/T \subseteq N$, set of pickup/delivery/transshipment terminals. $T_{w_1}^{w_2}$, set of terminals allows transshipments between mode 1 w_1 and mode 2 w_2.
K	Set of vehicles indexed by k and l. $K_{\text{b\&t}} \subseteq K$, set of barges and trains. $K_{\text{truck}} \subseteq K$, set of truck fleets. $K_w \subseteq K$, set of vehicles of mode w. $K_{\text{fix}} \subseteq K$, set of fixed vehicles.
A	Set of arcs. For $i, j \in N$, the arc from i to j is denoted by $(i, j) \in A$. $A_p/A_d \subseteq A$ represents the set of pickup/delivery arcs. For $(i, j) \in A_p$, $i \in P$. For $(i, j) \in A_d$, $j \in D$. $A_w \subseteq A$ represents the set of arcs for mode w. $A_{\text{fix}}^k \subseteq A$ represents the set of arcs for a fixed vehicle $k \in K_{\text{fix}}$.
I	Set of attributes.
Parameters:	
u_k	Capacity (TEU) of vehicle k.
q_r	Quantity (TEU) of request r.
τ_{ij}^k	The travel time (in hours) on arc (i, j) for vehicle k.
$[a_{p(r)}, b_{p(r)}]$	The pickup time window for request r.
$[a_{d(r)}, b_{d(r)}]$	The delivery time window for request r.
$[a_i^k, b_i^k]$	The open time window for fixed vehicle k at terminal i.
t''^k_i	The loading (or unloading) time (in hours) for vehicle k at terminal i.
v_k	Speed (km/h) of vehicle k.
d_{ij}^k	Distance (km) between terminals i and j for vehicle k.
e_k	The CO_2 emissions (kg) per container per km of vehicle k.
c_k^n	$c_k^1/c_k^{1'}$ are transport cost (euro) per hour/km per container using vehicle k. c_k^2 is the loading (or unloading) cost per container. c_k^3 is the storage cost per container per hour. c_k^4 is the carbon tax coefficient per ton. c_k^5 is the cost per hour of waiting time.
c_r^{delay}	The delay penalty per container per hour of request r.
M	A large enough positive number.
$\overline{S}$	Overall satisfaction benchmark.
$\overline{S_i}$	Satisfaction benchmark of attribute i.
Variables:	
x_{ij}^k	Binary variable; 1 if vehicle k uses the arc (i, j), 0 otherwise.
y_{ij}^{kr}	Binary variable; 1 if request r transported by vehicle k uses arc (i, j), 0 otherwise.
z_{ij}^k	Binary variable; 1 if terminal i precedes (not necessarily immediately) terminal j in the route of vehicle k, 0 otherwise.
s_{ir}^{kl}	Binary variable; 1 if request r is transferred from vehicle k to vehicle $l \neq k$ at transshipment terminal i, 0 otherwise.
$t_i^{kr}/t'^{kr}_i/\bar{t}_i^{kr}$	The arrival time/service start time/service finish time of request r served by vehicle k at terminal i.
$t_i^k/t'^k_i/\bar{t}_i^k$	The arrival time/last service start time/departure time of vehicle k at terminal i.
t_{ki}^{wait}	The waiting time of vehicle k at terminal i.
t_r^{delay}	The delay time of request r at delivery terminal.
S_i^r	Satisfaction value of request r and attribute i.
S^r	Overall satisfaction value of request r.

$$\sum_{j \in N} y_{ji}^{kr} - \sum_{j \in N} y_{ij}^{kr} \leqslant \sum_{l \in K} s_{ir}^{kl} \quad \forall k \in K,\ \forall r \in R,\ \forall i \in T \setminus p(r), d(r) \tag{11}$$

$$y_{ij}^{kr} \leqslant x_{ij}^k \quad \forall (i, j) \in A,\ \forall k \in K,\ \forall r \in R \tag{12}$$

Constraints (13) ensure that the transshipment occurs only once per transshipment terminal. Constraints (14) forbid transshipment between the same vehicle k.

$$\sum_{j \in N} y_{ji}^{kr} + \sum_{j \in N} y_{ij}^{lr} \leqslant s_{ir}^{kl} + 1 \quad \forall r \in R,\ \forall i \in T,\ \forall k, l \in K \tag{13}$$

$$s_{ir}^{kk} = 0 \quad \forall r \in R,\ \forall i \in T,\ \forall k \in K \tag{14}$$

Constraints (15)–(17) are the subtour elimination constraints and provide tight bounds in relatively short computation time among several polynomial-size versions of subtour elimination constraints (Öncan et al., 2009). Constraints (18) are the capacity constraints.

$$x_{ij}^k \leqslant z_{ij}^k \quad \forall i, j \in N,\ \forall k \in K_{\text{b\&t}} \tag{15}$$

$$z_{ij}^k + z_{ji}^k = 1 \quad \forall i, j \in N,\ \forall k \in K_{\text{b\&t}} \tag{16}$$

$$z_{ij}^k + z_{jp}^k + z_{pi}^k \leqslant 2 \quad \forall i,j,p \in N,\ \forall k \in K_{\text{b\&t}} \tag{17}$$

$$\sum_{r\in R} q_r y_{ij}^{kr} \leqslant u_k x_{ij}^k \quad \forall (i,j) \in A,\ \forall k \in K \tag{18}$$

Constraints (19) and (20) ensure vehicles running on suitable and predefined routes, respectively. Constraints (21) ensure the transshipment occurs in the right terminal.

$$x_{ij}^k = 0 \quad \forall k \in K_w,\ \forall (i,j) \in A \setminus A_w,\ \forall w \in W \tag{19}$$

$$x_{ij}^k = 0 \quad \forall k \in K_{\text{fix}},\ \forall (i,j) \in A \setminus A_{\text{fix}}^k \tag{20}$$

$$s_{ir}^{kl} = 0 \quad \forall k \in K_{w_1},\ \forall l \in K_{w_2},\ \forall i \in T \setminus T_{w_1}^{w_2},\ \forall r \in R,\ \forall w_1, w_2 \in W \tag{21}$$

Constraints (22)–(35) are temporal constraints. Constraints (22) and (23) are time constraints on service start and finish time, respectively. Constraints (24), (25), and (26) take care of the vehicle's arrival, service, and departure time, respectively.

$$t_i^{kr} \leqslant t'^{kr}_i \quad \forall i \in N,\ \forall k \in K,\ \forall r \in R \tag{22}$$

$$t'^{kr}_i + t''^{kr}_i \sum_{j\in N} y_{ij}^{kr} \leqslant \bar{t}_i^{kr} \quad \forall i \in N,\ \forall k \in K_{\text{b\&t}},\ \forall r \in R \tag{23}$$

$$t_i^k \leqslant t_i^{kr} \quad \forall i \in N,\ \forall k \in K_{\text{b\&t}},\ \forall r \in R \tag{24}$$

$$t'^k_i \geqslant t'^{kr}_i \quad \forall i \in N,\ \forall k \in K_{\text{b\&t}},\ \forall r \in R \tag{25}$$

$$\bar{t}_i^k \geqslant \bar{t}_i^{kr} \quad \forall i \in N,\ \forall k \in K_{\text{b\&t}},\ \forall r \in R \tag{26}$$

Constraints (27) and (28) ensure that the time on route of barges and trains is consistent with the distance traveled and speed, and Constraints (29) and (30) ensure the time on route of trucks. Constraints (31) and (32) take care of the time windows for pickup terminals and fixed terminals, respectively.

$$\bar{t}_i^k + \tau_{ij}^k - t_j^k \leqslant M(1 - x_{ij}^k) \quad \forall (i,j) \in A,\ \forall k \in K_{\text{b\&t}} \tag{27}$$

$$\bar{t}_i^k + \tau_{ij}^k - t_j^k \geqslant -M(1 - x_{ij}^k) \quad \forall (i,j) \in A,\ \forall k \in K_{\text{b\&t}} \tag{28}$$

$$\bar{t}_i^{kr} + \tau_{ij}^k - t_j^{kr} \leqslant M(1 - y_{ij}^{kr}) \quad \forall (i,j) \in A,\ \forall k \in K_{\text{truck}} \tag{29}$$

$$\bar{t}_i^{kr} + \tau_{ij}^k - t_j^{kr} \geqslant -M(1 - y_{ij}^{kr}) \quad \forall (i,j) \in A,\ \forall k \in K_{\text{truck}} \tag{30}$$

$$t'^{kr}_{p(r)} \geqslant a_{p(r)} y_{ij}^{kr},\ \bar{t}_{p(r)}^{kr} \leqslant b_{p(r)} + M(1 - y_{ij}^{kr}) \quad \forall (i,j) \in A, \forall r \in R,\ \forall k \in K \tag{31}$$

$$t_i^{kr} \geqslant a_i^k y_{ij}^{kr},\ \bar{t}_i^{kr} \leqslant b_i^k + M(1 - y_{ij}^{kr}) \quad \forall (i,j) \in A,\ \forall r \in R,\ \forall k \in K_{\text{fix}} \tag{32}$$

Constraints (33) are time constraints for transshipment. If there is a transshipment from vehicle k to vehicle l, but vehicle l arrives before vehicle k departs, vehicle l can wait until vehicle k completes its unloading. Constraints (34) and (35) calculate waiting time and delay time, respectively.

$$\bar{t}_i^{kr} - t'^{lr}_i \leqslant M(1 - s_{ir}^{kl}) \quad \forall r \in R,\ \forall i \in T,\ \forall k,l \in K,\ k \neq l \tag{33}$$

$$t_{ki}^{\text{wait}} \geqslant t'^k_i - t_i^k \quad \forall i \in N,\ \forall k \in K_{\text{b\&t}} \tag{34}$$

$$t_r^{\text{delay}} \geqslant (\bar{t}_{d(r)}^{kr} - b_{d(r)}) \sum_{i\in N} y_{id(r)}^{kr} \quad \forall r \in R,\ \forall k \in K \tag{35}$$

Constraints (36) and (37) set variables x and y as binary variables.

$$x_{ij}^k \in \{0,1\} \quad \forall (i,j) \in A,\ \forall k \in K \tag{36}$$

$$y_{ij}^{kr} \in \{0,1\} \quad \forall (i,j) \in A,\ \forall k \in K,\ \forall r \in R \tag{37}$$

Constraints (38)/(39) ensure that absolute/relative preferences are respected (the meanings of absolute/relative preferences will be introduced in Section 4.2). $\overline{S_i}$ and $\overline{S}$ are the predefined satisfaction benchmark of attribute i and overall satisfaction benchmark, respectively.

$$S_i^r \geqslant \overline{S_i} \quad \forall r \in R,\ \forall i \in I \tag{38}$$

$$S^r \geqslant \overline{S} \quad \forall r \in R \tag{39}$$

4.2. Satisfaction calculation for HVP

This section aims to obtain the satisfaction S_i^r/S^r in Constraints (38)/(39) according to preferences of shippers. The fuzzy set theory can be used to handle linguistic preferences. Fuzzy set theory captures the subjectivity of human behavior and model imprecision arising from mental phenomena which are neither random nor stochastic (Chen and Hwang, 1992). Compared with simple value ranges, which obtain results following crisp "true"/"false" logic, fuzzy set theory expresses the "truthiness" as partially true or partially false. Section 4.2.1 introduces the considered attributes and related fuzzy sets.

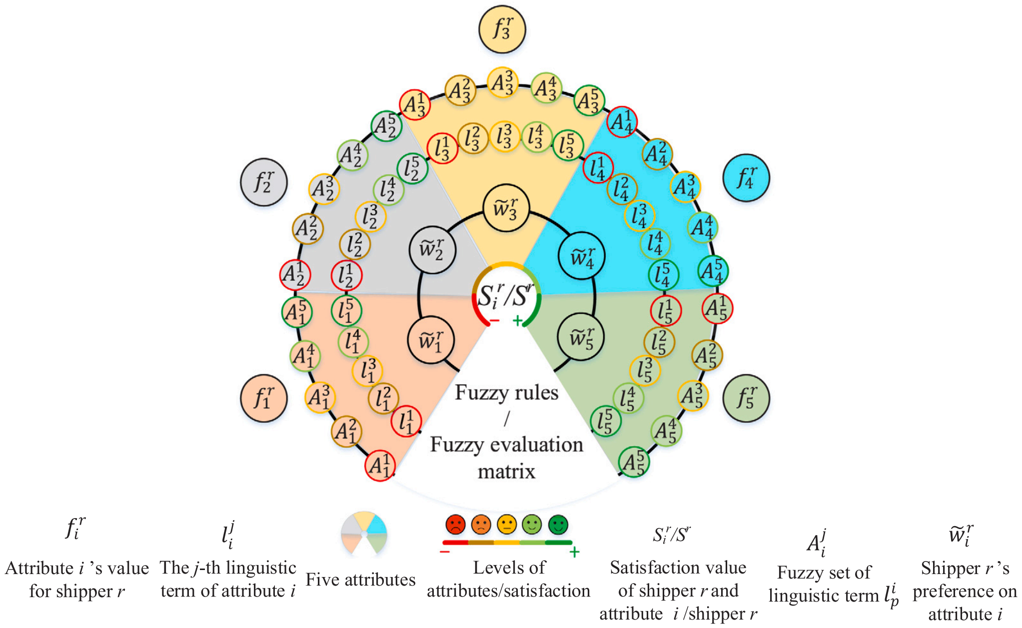


Fig. 4. Multiple attributes and fuzzy variables.

Different shippers may express their preferences over attributes by means of different linguistic terms. The given preference information could typically be of two types: absolute and relative preferences. The absolute preferences mean that shippers give concrete preferences on attributes, e.g., they need containers to be transported in a "low-cost" (Cost attribute) and "very reliable" (Reliability attribute) way. Relative preferences mean that shippers express the importance of different attributes, e.g., they may say minimizing cost and emissions are "very important" and reducing risk is "not important" for them. The ranking of attributes is one type of relative preferences, for example, the first-ranked and second-ranked attributes can be regarded as "very important" and "important", respectively. Section 4.2.2 presents the steps to calculate satisfaction under absolute preference. Since the approach for relative preferences has similar steps, it is presented in Appendix C.

4.2.1. Multiple attributes and fuzzy variables

Fig. 4 shows the multiple attributes and fuzzy variables with linguistic terms and fuzzy sets. Shipper r has vague preferences $\tilde{w}_i^r$ towards attribute i. We obtain attribute value f_i^r for each attribute, then calculate satisfaction value S_i^r/S^r through MADM approaches.

An attribute i can be defined as a fuzzy variable, such as Cost or Time. The fuzzy variable has a predefined value range and several linguistic terms that are used to describe the variable. We use l_i^j to represent the jth linguistic term of attribute i. Take the cost attribute as an example, its value range could be [0, 1.8], and linguistic terms are adjectives like "low-cost", "medium", and "expensive". The value in the value range is called *crisp value*, which is how we think of the variable numerically, e.g., 1 euro/km/TEU for the cost attribute. A linguistic term l_i^j corresponds to a fuzzy set A_i^j, which is a pair (U, μ), where U is referred to as the universe of discourse and μ is a membership function. For each $x \in U$, the value $\mu(x)$ is called the grade of membership of x, which means the degree of truth to the term. For example, 1 euro/km/TEU's grades to "expensive" and "very expensive" could be 0.8 and 0.2, respectively. The trapezoidal and triangular membership functions are used in this paper, where the triangular membership function is a special trapezoidal membership function. The trapezoidal membership function is given in Eq. (40) with a trapezoidal fuzzy number (a, b, c, d), whereby $a \le b \le c \le d$ and $b = c$ for the triangular membership function:

$$\mu(x) = \begin{cases} 0, & x < a \\ \dfrac{(x-a)}{(b-a)}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{(d-x)}{(d-c)}, & c \le x \le d \\ 0, & x > d \end{cases} \tag{40}$$

In this research, important attributes in synchromodal transport are selected according to two surveys and an interview, as shown in Table 3. In the interview and surveys, we receive a total of 13 responses from shippers, freight forwarders, and carriers in different intermodal/synchromodal transport companies, and the results are shown in Table 3. Cost and Reliability are the two

Table 3
The chosen attributes in this study.

Attribute	Definition	Unit	Importance[a]	Sources
1: Cost	The cost of shipping one TEU (20-foot container)one km from origin to destination	euro	71% L_1, 29% L_2	survey 2, interview
2: Time	The ratio of actual time between the origin and destination to expected time	percentage	46% L_1, 31% L_2, 23% L_3	survey 1&2, interview
3: Reliability	The ratio of the delay time to total travel time	percentage	77% L_1, 23% L_2	survey 1&2, interview
4: Emissions	CO_2 emitted per container per km	kg	23% L_2, 39% L_3, 15% L_4, 23% L_5	survey 1&2, interview
5: Risk of damage	The number of containers transferred from one vehicle to another vehicle	TEU	29% L_1, 57% L_3, 14% L_4	survey 2, interview

[a]The importance evaluation is from respondents in all related sources.
L_1, L_2, L_3, L_4, and L_5: importance levels representing extremely, very, moderately, slightly, and not at all important, respectively.
survey 1: in the "Novel inland waterway transport concepts for moving freight effectively" (NOVIMOVE) project, we designed the first survey and received six reactions from shippers/freight forwarders (Ramos et al., 2020).
survey 2: we designed the second survey (https://freeonlinesurveys.com/s/DZS7QlrE) and received three responses from a shipper in FAW-Volkswagen Automotive Co. Ltd, a shipper in China Railway Materials Trade company, and a carrier in China International Marine Containers (Group) Co. Ltd.
interview: we interviewed three freight forwarders in China Railway Container Transport Co. Ltd. and one shipper in China National Fisheries Corporation.

most important attributes, followed by the Time attribute. Compared with passenger transportation, the probability of damage on the cargoes is quite higher because of multiple handling operations during freight transportation, especially at transshipment terminals. Therefore, Risk of damage is also an important attribute, and the "number of transferred containers" is used here to represent it because more transshipments may cause more cargo damage. For the Emission attribute, respondents agree that it is important if there is a sustainability policy from the government, especially for large companies. Both Europe and China have such policies (Kallas, 2011; State Council of China, 2021). The proposed model can be extended to work with other attributes (such as flexibility and frequency) when needed.

For request r, the actual travel time is:

$$t_r = \max\{\bar{t}_i^{kr} y_{ij}^{kr} : \forall (i,j) \in A, \ \forall k \in K\} - \min\{t'^{kr}_i y_{ij}^{kr} : \forall (i,j) \in A, \ \forall k \in K\} \tag{41}$$

The values of five attributes are calculated according to Eqs. (42) to (46).

$$f_1^r = F_2^r / (q_r \sum_{k \in K} \sum_{(i,j) \in A} d_{ij}^k y_{ij}^{kr}) \tag{42}$$

$$f_2^r = t_r / (d_{p(r)d(r)}^{\text{average}} / v_{\text{average}}) \tag{43}$$

$$f_3^r = \max\{0, (t_r^{\text{delay}} - \max\{\bar{t}_i^{kr} y_{ij}^{kr} : \forall (i,j) \in A, \ \forall k \in K\})\} / t_r \tag{44}$$

$$f_4^r = \sum_{k \in K} \sum_{(i,j) \in A} e_k y_{ij}^{kr} q_r d_{ij}^k / (q_r \sum_{k \in K} \sum_{(i,j) \in A} d_{ij}^k y_{ij}^{kr}) \tag{45}$$

$$f_5^r = \sum_{k,l \in K, k \neq l} \sum_{i \in T} s_{ir}^{kl} q_r \tag{46}$$

where F_2^r is the overall cost of request r and the calculation of F_2^r is similar to Eq. (2). The expected travel time is calculated by the average travel distance of all vehicles $d_{p(r)d(r)}^{\text{average}}$ divided by the average speed of all vehicles v_{average}.

4.2.2. Satisfaction calculation under absolute preferences

The satisfaction value of each attribute S_i^r is calculated when shippers express absolute preferences:

$$S_i^r = Fuzzy(f_i^r, \tilde{w}_i^r) \tag{47}$$

where $Fuzzy()$ represents the MADM approach for absolute preferences. The satisfaction value S_i^r is obtained according to the following steps.

Step 1: handle the shipper's vague preferences towards attributes. We define five levels for linguistic terms l_i^j of absolute preferences, as shown in Fig. 5(a). For example, Level 1 for Cost/Reliability attribute means "very low cost"/"very reliable", and Level 4 for Time/Risk of damage attribute means "slow"/"high risk". Fig. 5(a) also shows the membership function μ for five levels. The membership functions of attributes are different because the value ranges U of attributes are different.

Step 2: obtain the actual attribute value's level. After obtaining the attribute value f_i^r, the memberships to levels are determined. Specific fuzzy numbers of levels used in this paper are shown in Table 5 in Section 6.

Step 3: link the preference, attribute value, and satisfaction. The satisfaction is also set as a fuzzy variable, as shown in Fig. 5(b). Fuzzy variables for attributes and satisfaction are linked by a set of fuzzy rules, which are IF-THEN statements. The same

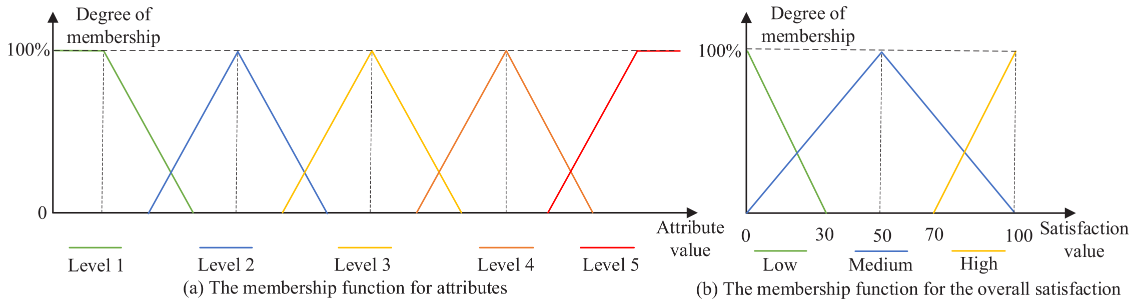


Fig. 5. The membership functions for attributes and the overall satisfaction.

attribute value may lead to different satisfaction because shippers have different preferred levels. For example, if shipper 1 prefers "low" cost and shipper 2 prefers "medium" cost, shipper 2 will be more satisfied than shipper 1 when the actual cost is "low".

When the preferred level is the highest level, the fuzzy rule is:

IF the level of the attribute i *equals/is lower than* the highest level $\tilde{w}_i^r$, THEN the satisfaction will be *high/low*.

When the preferred level is the lowest level, the fuzzy rule is:

IF the level of the attribute i *is higher than/equals* the lowest level $\tilde{w}_i^r$, THEN the satisfaction will be *high/medium*.

When calculating the satisfaction value for a specific attribute and the preferred level is neither the highest nor lowest level, the fuzzy rule is:

IF the level of the attribute i *is higher than/equals/is lower than* the preferred level $\tilde{w}_i^r$, THEN the satisfaction will be *high/medium/low*.

For the preference constraints, the satisfaction value of each attribute S_i^r is calculated by Eq. (47) through fuzzy rules for one attribute. When calculating the satisfaction value of h attributes, a set of rules for these attributes will be used, as shown in Eq. (48).

$$S^r = Fuzzy(f_1^r, \tilde{w}_1^r, \ldots, f_n^r, \tilde{w}_h^r) \tag{48}$$

Step 4: calculate the satisfaction value by defuzzification. After defining fuzzy variables and fuzzy rules, the satisfaction value can be obtained using a defuzzification method, such as Center of Gravity used in this paper (Van Leekwijck and Kerre, 1999).

5. The ALNS heuristic for the STPP-HVP

As verified in Appendix A, solving the proposed problem to optimality using an exact approach (Gurobi) is computationally expensive. The Adaptive Large Neighborhood Search (ALNS) has been applied to Vehicle Routing Problems successfully due to its flexibility in choosing different operators to achieve the exploration and exploitation in the searching space (Qu and Bard, 2012; Masson et al., 2013; Grangier et al., 2016). The results in Aksen et al. (2014), de Sá et al. (2015), and Dayarian et al. (2016) also show that exact algorithms are unable to provide the optimal solution for the large instances due to the complexity increase, while the ALNS produces high-quality solutions with low computation time. Zhang et al. (2022b) verify that ALNS can obtain the (near) optimal solution for synchromodal transport planning and it performs well on large-scale instances. Therefore, a customized ALNS is developed to solve the STPP-HVP. The pseudocode of the ALNS that is developed for our problem is given in Algorithm 1. This paper uses Greedy Insertion, Random Insertion, Transshipment Insertion, Most Constrained First Insertion, Regret Insertion, Worst Removal, Random Removal, Node Removal, Route Removal, Related Removal, and History Removal operators. The operators and adaptive mechanism of the ALNS are illustrated in detail in the literature (Ropke and Pisinger, 2006) as well as our previous papers (Zhang et al., 2022a,b) and will not be repeated in this paper. Compared with our previous papers, the ALNS in this study is customized as follows: (a) requests are allowed not to be served if preferences cannot be met (lines 2 and 15–17); (b) the synchronization methods considering time and preferences constraints (will be introduced in Algorithm 2) are added in the removal and insertion operators (lines 7, 10, and 14); (c) the best solution is judged according to objectives F_1 and F_2 (lines 19–32). Moreover, this algorithm can be extended to a re-planning algorithm and detailed information can be found in Appendix B.

The following constraints need to be checked in the ALNS: subtour elimination constraints (15)–(17), capacity constraints (18), suitable routes constraints (19), time constraints (22)–(35), and preference constraints (38)/(39). Other constraints are satisfied automatically in the construction of routes, such as flow conservation (7)–(12). The subtour elimination constraints can be guaranteed by checking whether there are duplicate terminals on the route. When picking up/delivering requests, the current load will increase/decrease by the quantity q_r. If the current load exceeds the capacity of the vehicle, the capacity constraints will be violated. The suitable routes constraints are ensured by checking whether the adjacent terminals in the routes are the same as unsuitable routes.

The difficulty lies in satisfying the time and preferences constraints, especially when vehicles depend on each other due to transshipment, as shown in Fig. 6. Vehicles $l_1 - -l_3$ load containers unloaded by vehicle k_1, therefore the changes on route of vehicle k_1 will influence vehicles $l_1 - -l_3$. The routes of vehicles $l_1 - -l_3$ are called relevant routes of vehicle k_1. Similarly, routes of vehicles

Algorithm 1: The ALNS algorithm

Input: K, R, N, A, X_{current}; **Output:** $X_{\textbf{best}}$; // $X_{\text{current}}/X_{\text{best}}$ means the current/best solution.
define the set of unserved requests as R_{pool} ; // R_{pool} represents the request pool.
obtain initial solution X_{initial}; set $T_{\text{Temp}} > 0$ depending on X_{initial};
$X_{\text{last}} \leftarrow X_{\text{initial}}$; $X_{\text{best}} \leftarrow X_{\text{last}}$; // X_{last} means the last solution.
repeat
  refresh weights and choose operators depending on weights at the beginning of each segment;
  $X_{\text{current}} \leftarrow X_{\text{last}}$; $[X_{\text{current}}, R_{\text{pool}}] = RemovalOperator(X_{\text{current}}, R_{\text{pool}})$; $flag = False$;
  while *R_{pool} is not empty* **do**
    if $flag == True$ **then**
      $[X_{\text{current}}, R_{\text{pool}}] = RemovalOperator(X_{\text{current}}, R_{\text{pool}})$
    else
      $flag = True$
    end
    $[X_{\text{current}}, R_{\text{pool}}] = InsertionOperator(X_{\text{current}}, R_{\text{pool}})$;
    if *the number of loops of trying to empty R_{pool} exceeds the preset value* **then**
      break;
    end
  end
  if $F_1(X_{current}) > F_1(X_{last})$ **then**
    $X_{\text{last}} \leftarrow X_{\text{current}}$;
  else
    if $F_1(X_{current}) = F_1(X_{last})$ **then**
      if $F_2(X_{current}) < F_2(X_{last})$ **then**
        $X_{\text{last}} \leftarrow X_{\text{current}}$;
      else
        $X_{\text{last}} \leftarrow X_{\text{current}}$ with probability $p = e^{\frac{-(F_2(X_{\text{current}})-F_2(X_{\text{last}}))}{T_{\text{Temp}}}}$; // Update X_{last} by the simulated annealing (Ropke and Pisinger, 2006).
      end
    end
  end
  if $F_1(X_{last}) > F_1(X_{best})$ *or* ($F_1(X_{last}) = F_1(X_{best})$ *and* $F_2(X_{last}) < F_2(X_{best})$) **then**
    $X_{\text{best}} \leftarrow X_{\text{last}}$;
  end
  $T_{\text{Temp}} \leftarrow T_{\text{Temp}} \cdot c$; // c is the cooling rate.
until *the predefined number of iterations is reached*;

$m_1 - m_3/m_4 - m_6/m_7 - m_9$ are relevant routes of vehicle $l_1/l_2/l_3$. A small change of a vehicle will cause a chain reaction on relevant routes. The synchronization means that if a vehicle influences other vehicles, these vehicles' schedules will be re-planned and vehicles could cooperate to obtain the best solution. Such cooperation could be changing pickup/delivery time or extending/shortening the waiting or storage time. Moreover, the preference information needs to be checked during the synchronization to guarantee shippers are satisfied. For example, when a new request r_2 is inserted into the route of vehicle l_2, the request r_1 will be influenced because it is transported by the relevant route of vehicle m_5, and the satisfaction value of r_2 will be recalculated using information of k_1, l_2, and m_5. Algorithm 2 shows the synchronization on relevant routes, in which the initial input is the original changed route. To check all relevant routes shown in Fig. 6, this function is a recursion function. If all relevant routes meet the time and preference constraints, the current solution is feasible, otherwise, the synchronization will stop and return "infeasible".

6. Case study

This section evaluates the proposed model in various scenarios by comparing it with different benchmarks. Section 6.1 describes the settings in case studies and Section 6.2 analyzes results.

6.1. The transport network and instances

The European Gateway Services (EGS) network is selected as the real-world case to test the proposed model through simulation experiments. EGS network is located at Rhine-Alpine corridor, which constitutes one of the busiest freight routes in Europe, around 138 billion tonne-kilometers freight is transported along this corridor annually, accounting for 19% of total GDP of the EU. Fig. 7 presents the overall network of this study (Guo et al., 2020). It contains three terminals in the Port of Rotterdam and seven inland terminals in the Netherlands, Belgium, and Germany. In total 116 vehicles are used in the case study, which includes 49 barges, 33 trains, and 34 truck fleets. The origins and destinations of requests are distributed randomly among deep-sea terminals and

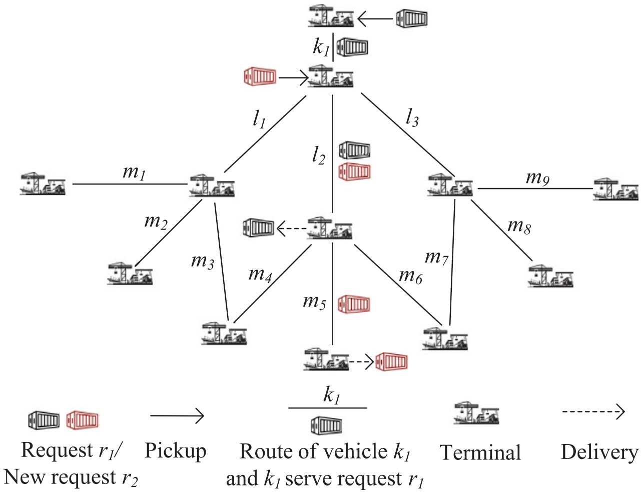


Fig. 6. Synchronization and preference checking.

Algorithm 2: Synchronization

```
Input: relevant_routes; Output: feasibility;
for route of vehicle k ∈ relevant_routes do
    update pickup/delivery time and extend/shorten the waiting or storage time of influenced requests;
    if route of vehicle k does not satisfy time constraints then
        return infeasible
    else
        for request r served by vehicle k do
            obtain the vehicles that serve request r;
            calculate the satisfaction value of request r;
            if request r does not satisfy the preference constraints then
                return infeasible
            end
        end
        obtain relevant_routes of route k;
        Synchronization(relevant_routes)
    end
end
return feasible;
```

inland terminals, respectively. The container volumes of requests are drawn independently from a uniform distribution with range [10, 30] (unit: TEU). The time horizon of the transport planning is eight days. Before the transport, the model is used to generate transport plans for all requests. If unexpected events occur during the transportation, the model will be triggered for the re-planning of influenced schedules. The earliest pickup time $a_{p(r)}$ of requests is drawn independently from a uniform distribution with range [1, 120]; the latest delivery time $b_{d(r)} = a_{p(r)} + LD_r$, where LD_r is the lead time and it is independently and identically distributed among 24, 48, 72 (unit: hours) with probabilities 0.15, 0.6, 0.25. Moreover, we set $b_{p(r)}$ and $a_{d(r)}$ equal to $b_{d(r)}$ and $a_{p(r)}$, respectively. Detailed information on how the instances are generated can be found in Guo et al. (2020). Specific parameters are shown in Table 4. All instances and detailed results are available at a research data website.[1] Since the insights obtained from results under absolute and relative preferences are similar, this section only shows results under absolute preferences, and results under relative preferences are reported in Appendix C.

According to the average attribute values of all modes in the EGS network, the fuzzy numbers are set as in Table 5. For Cost, Time, and Emissions attributes, the values of Levels 1, 3, and 5 are calculated according to the minimum, average, and maximum values using any mode/mode combination, respectively. The values of Levels 2 and 4 are obtained based on other levels with a value interval of 0.3. For the Reliability attribute, a maximum 15% delay (Level 5) is allowed, and other Levels are obtained with a value interval of 3%. Depending on the maximum number of containers in instances, we define the maximum value (Level 5) of the Risk attribute as 150 and values at other Levels are obtained with a value interval of 30. Experiments of using varying fuzzy

[1] https://figshare.com/s/e1631bc804deed885d43.

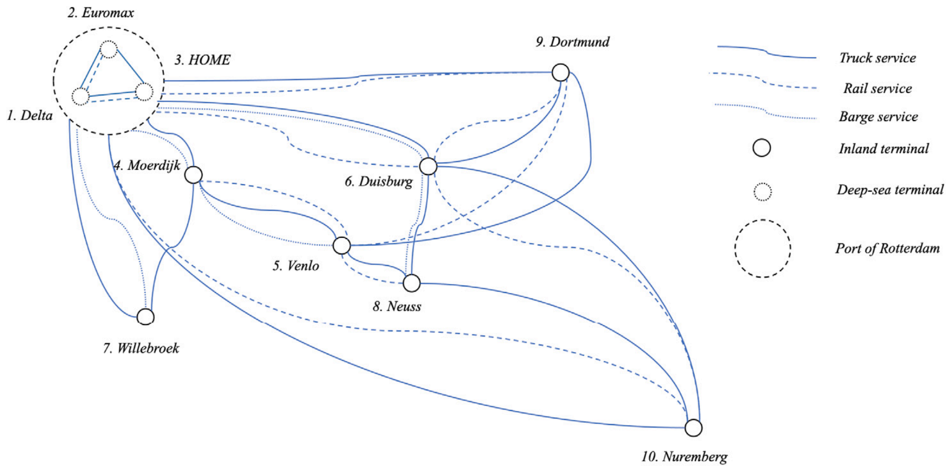


Fig. 7. EGS transport network.
Source: Guo et al. (2020).

Table 4
Parameters used in the paper.

Parameter	Value	Parameter	Value	Parameter	Value
c^1_{truck}	30.98	c^1_{train}	7.54	c^1_{barge}	0.6122
$c^{1'}_{\text{truck}}$	0.2758	$c^{1'}_{\text{train}}$	0.0635	$c^{1'}_{\text{barge}}$	0.0213
c^2_{truck}	3	c^2_{train}	18	c^2_{barge}	18
c^3_k	1	c^4_k	8	c^5_k	1
e_{truck}	0.8866	e_{train}	0.3146	e_{barge}	0.2288
$\overline{S}$	8.1	$\overline{S_i}$	50		

Table 5
Trapezoidal fuzzy numbers $\tilde{w'}^j_i$ on specific levels.

Level	Cost	Time	Reliability	Emissions	Risk of damage
Level 1	[0.0,0.0,0.3,0.5]	[0.0,0.0,0.5,0.7]	[0.00,0.00,0.01,0.03]	[0.0,0.3,0.3,0.5]	[0,0,10,30]
Level 2	[0.4,0.6,0.6,0.8]	[0.6,0.8,0.8,1.0]	[0.02,0.04,0.04,0.06]	[0.4,0.6,0.6,0.8]	[20,40,40,60]
Level 3	[0.7,0.9,0.9,1.1]	[0.9,1.1,1.1,1.3]	[0.05,0.07,0.07,0.09]	[0.7,0.9,0.9,1.1]	[50,70,70,90]
Level 4	[1.0,1.2,1.2,1.4]	[1.2,1.4,1.4,1.6]	[0.08,0.10,0.10,0.12]	[1.0,1.2,1.2,1.4]	[80,100,100,120]
Level 5	[1.3,1.5,1.8,1.8]	[1.5,1.7,2.2,2.2]	[0.11,0.13,0.15,0.15]	[1.3,1.5,1.8,1.8]	[110,130,150,150]

numbers are also performed. Since similar insights are obtained, this section only presents results using fuzzy numbers in Table 5 to avoid repetition.

Several scenarios are designed to analyze the impact of considering shippers' preferences in the freight forwarder's transport planning, including a benchmark where preferences are ignored, five scenarios of homogeneous preferences on five attributes, and six scenarios of heterogeneous preferences. In the benchmark scenario, Constraints (38)/(39) are not applied. In each scenario, results under hard constraints, fuzzy constraints, and the satisfaction objective are compared. Under hard constraints, if the attribute value of an alternative is lower than the middle value in the fuzzy number, the alternative is accepted by the ALNS, otherwise is rejected. Take the Cost attribute in Table 5 as an example, the middle values for Level 1 to Level 5 are 0.3, 0.6, 0.9, 1.2, and 1.5, respectively. In the literature, besides studies like our study that improve service levels by setting preferences as constraints (Dumez et al., 2021; Zhang et al., 2013), some studies consider preferences in the objective by minimizing the sum of costs and dissatisfaction (Los et al., 2018; Baniamerian et al., 2018). It is interesting to compare these two ways of handling preferences. Therefore, we have compared the proposed method with the method in Los et al. (2018) and Baniamerian et al. (2018) (it is called the satisfaction objective method hereinafter). When considering preferences in the objective, Constraints (38)/(39) are not considered and the objective F_2 is replaced by the objective F_3:

$$F_3 = norm(F_2) - norm(\sum_{r \in R} S^r) \tag{49}$$

where $norm()$ is the min–max normalization function that transforms costs and satisfaction values to be on a similar scale.

The preferences data are randomly generated according to the proportion of different types of shippers, such as cost-sensitive and reliability-sensitive shippers. In the scenario with homogeneous preferences, it is as if there is only one type of shipper,

Table 6
Average computation time (s).

Number of requests	Homogeneous preferences				Heterogeneous preferences			
	ignore	hard	fuzzy	obj	ignore	hard	fuzzy	obj
5	0.2	0.3	1.7	3.3	0.3	0.2	2.2	3.3
10	0.7	2.9	72.7	45.4	0.7	1.2	28.8	31.3
20	1.7	1.4	13.1	70.7	1.6	1.5	12.7	82.8
30	4.0	25.0	16.7	194.6	3.3	7.7	785.4	243.1
50	10.2	26.2	29.2	463.0	5.5	78.3	594.4	509.2
100	51.8	200.0	4332.5	638.8	15.8	247.5	2076.5	388.9

Ignore: experiments that ignore preferences; hard/fuzzy: experiments considering hard/fuzzy constraints; obj: experiments with the satisfaction objective.

which means all shippers have similar preferences, such as low-cost or fast transport. However, their preferences are not totally the same because some shippers have higher requirements than others. In the scenario with heterogeneous preferences, there are different proportions of shippers with heterogeneous preferences depending on their cargo types or company features. Cargoes requiring low-cost, fast, reliable, low-risk, and sustainable transport are mixed in all requests. We consider six scenarios, i.e., heter. 1/2/3/4/5/6, which mean the proportions of shippers that prefer attributes are: [Cost, Time, Reliability, Risk of damage, Emissions] = [0.2,0.2,0.2,0.2,0.2]/[0.5,0.1,0.1,0.1,0.2] /[0.2,0.5,0.1,0.1,0.1]/[0.2,0.1,0.5,0.1,0.1]/[0.2,0.1,0.1,0.5,0.1]/[0.2,0.1,0.1,0.1,0.5]. The results in this section are obtained under a setting that all vehicles have fixed services, i.e., all vehicles follow predefined routes and schedules.

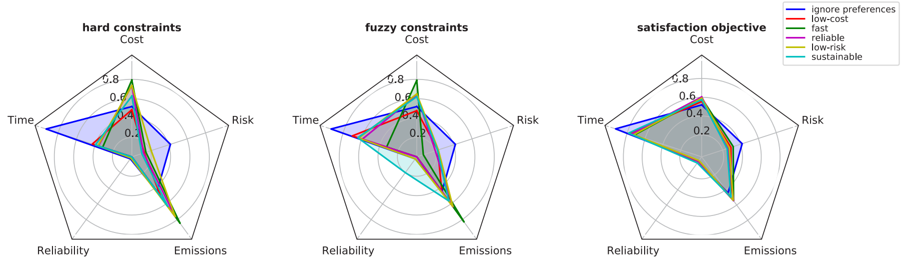
6.2. Results under homogeneous and heterogeneous preferences

Table 6 shows the average computation time for different instances. There is a trend that the computation time increases when the number of requests increases. The computation time when using fuzzy constraints or satisfaction objective is usually higher than others because handling vague preferences needs more time. However, there is no obvious difference between the computation time of experiments considering homogeneous and heterogeneous preferences.

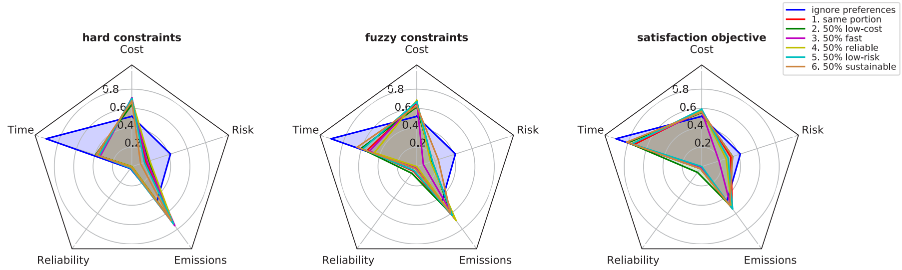
Based on the results in Fig. 8, relationships between preferences and attributes (Cost, Time, Reliability, Emissions, and Risk) are analyzed. The attribute value is improved when the shipper has a higher requirement on this attribute. For example, in Fig. 8(a), when a shipper wants fast transport because the product is perishable, more trucks are used and the transport time decreases compared with the benchmark which ignores preferences. Under heterogeneous preferences in Fig. 8(b), the freight forwarder needs to trade-off the different preferences of shippers. Therefore, the results do not have as significant as an improvement on a specific attribute compared with results under homogeneous preferences. When shippers have requirements on conflicting attributes, the freight forwarder will find a trade-off between these attributes by making each attribute better without making any other attribute worse than the expectation of shippers. Attributes may reinforce each other. Both low-cost and fast transport needs unimodal transport (barge or truck), so there are fewer transshipments and lower risk of damage, and their risks are even lower than the case when shippers prefer low-risk transport, as shown in both Figs. 8(a) and 8(b). The costs under fuzzy attributes are higher than costs under the satisfaction objective except for the case that all shippers prefer low-cost transport. However, the values of preferred attributes are lower under fuzzy attributes and shippers are more satisfied.

Fig. 9 shows mode shares (Barge, Train, Truck) across different preferences. In Fig. 9(a), compared with other preferences, the mode shares of barges and trains are larger when shippers prefer low-cost and sustainable transport. When all shippers prefer fast transport in Fig. 9(a), the mode shares of trains and trucks, especially trucks, increase substantially compared with the benchmark. When shippers prefer reliable transport in Fig. 9(a), the mode share of trucks increases compared with low-cost and sustainable transport, but the increase is not as significant as the fast transport, because reliable transport focuses on delay rather than total time. When considering preferences, the mode share of barges is smaller than the benchmark because barges not only have advantages (low-cost and low-emissions) but also disadvantages (slow), which make barges unsuitable to resolve conflicts. Under fuzzy constraints, the freight forwarder has more room to reduce costs when satisfying the preferences of shippers, therefore the mode share of barges is usually higher than under hard constraints. Satisfaction is no longer the constraint under the satisfaction objective method. Solutions that have lower costs and higher dissatisfaction rather than higher cost and lower satisfaction are chosen, therefore the mode share of barges under the satisfaction objective method is always higher than other methods. When 50% of shippers prefer low-cost (heter. 2) or sustainable transport (heter. 6) in Fig. 9(b), more trucks are used compared with the mode share under homogeneous preferences in Fig. 9(a), because there are the remaining 50% of shippers with other preferences under the heterogeneous case. The fast transport scenarios in Figs. 9(a) and 9(b) show the opposite phenomenon. In summary, based on our parameter settings, using more trucks benefits fast, reliable, and low-risk transport, whereas low-cost and sustainable transports need more barges, and trains are preferred when considering conflicting attributes or preferences.

Fig. 10 shows the number of served requests (N), the number of requests that satisfy fuzzy constraints (F), and those that satisfy hard constraints (H) across different preferences. All requests can be served when preferences are not considered. This is not the case under hard preferences and N is in between the two under fuzzy constraints. When using fuzzy constraints, the proportion of satisfied shippers is the largest. Both F and H increase after considering preferences except Fig. 10(b), where N decreases because of hard constraints. H under fuzzy constraints is usually less than H under hard constraints due to two reasons: (i) more requests are

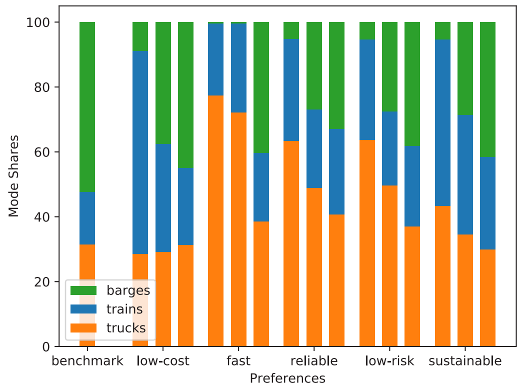


(a) Homogeneous preferences

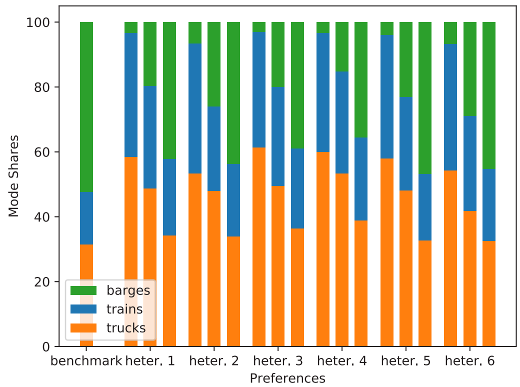


(b) Heterogeneous preferences

Fig. 8. Radar charts of five attributes across homogeneous and heterogeneous preferences.



(a) Homogeneous preferences



(b) Heterogeneous preferences

Fig. 9. Mode shares under homogeneous and heterogeneous preferences. The three bars from left to right of each instance are results under hard constraints, fuzzy constraints, and the satisfaction objective, respectively.

served under fuzzy constraints, but the used resources are the same with hard constraints, therefore service quality for each request is not as high as before; (ii) the freight forwarder has more room to minimize cost under fuzzy constraints, which deteriorates service quality a bit. Compared with considering preferences in constraints, the number of served requests (N) is higher under the satisfaction objective, while the number of requests that respect shippers' preferences (F and H) is lower.

The average satisfaction values (S) are shown in Fig. 11. Under hard constraints, only those requests that can be fully satisfied are served, therefore S is always 100 and is not shown in Fig. 11. When considering preferences, satisfaction values of shippers increase significantly compared with the cases that ignore preferences (N). S under fuzzy constraints (F) is less than 90 because the freight forwarder wants to minimize transport cost when the shippers' vague preferences are satisfied, which usually reduces the quality of services. Therefore, the freight forwarder's objective of minimizing cost is not ignored in the proposed model, especially when using fuzzy constraints. The satisfaction values under the satisfaction objective (O) are usually lower than the ones under fuzzy constraints (F) because the satisfaction is sacrificed to obtain lower cost when satisfaction is considered in the objective instead of constraints. Therefore, when the freight forwarder wants to ensure shippers' satisfaction, it is better to consider preferences in constraints.

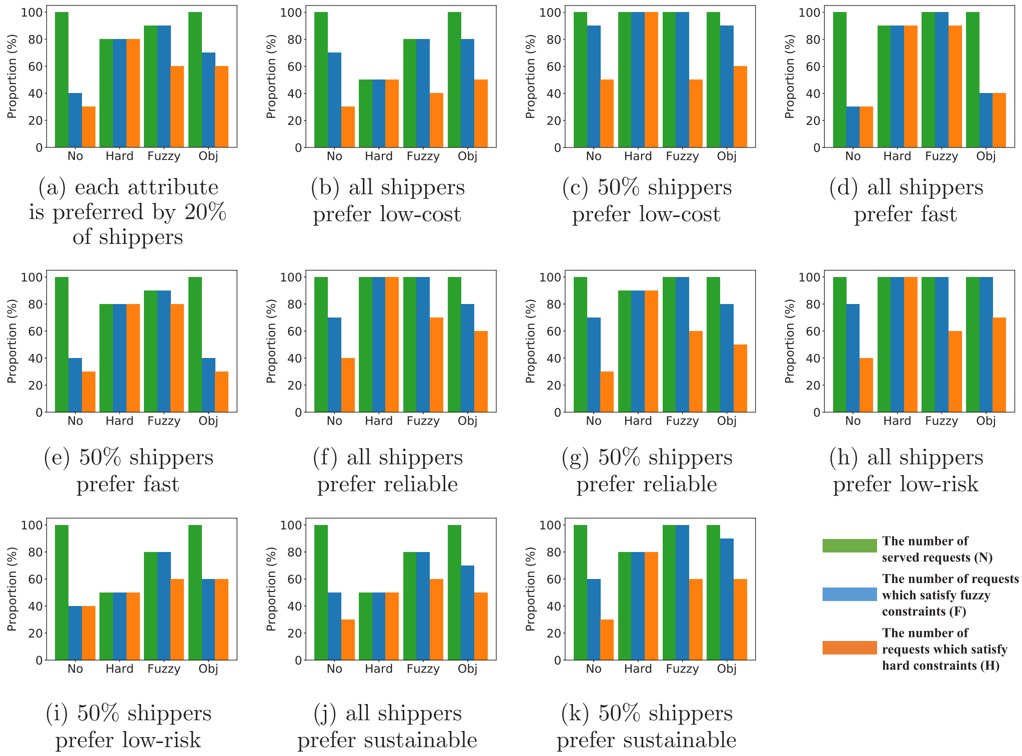


Fig. 10. Proportion (%) of served requests across different preferences. "No", "Hard", "Fuzzy", and "Obj" mean results under no preference constraints, hard constraints, fuzzy constraints, and the satisfaction objective, respectively.

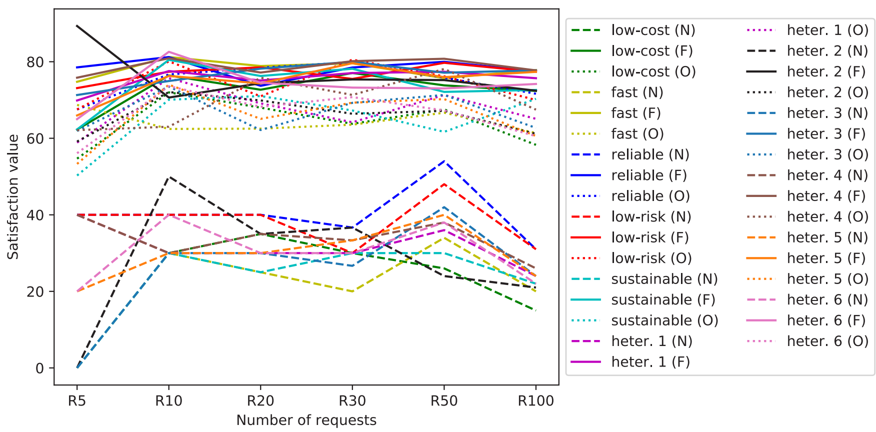


Fig. 11. Satisfaction values under no preference constraints (N), fuzzy constraints (F), and the satisfaction objective (O) across different preferences.

7. Conclusions and future directions

In this paper, an optimization model is established for the Synchromodal Transport Planning Problem with Heterogeneous and Vague Preferences (STPP-HVP). Two typical types of linguistic terms, i.e., absolute and relative preferences are considered. The mathematical model is proposed to formulate the STPP-HVP and Multiple Attribute Decision Making integrating fuzzy set theory is used to model heterogeneous and vague preferences. A customized Adaptive Large Neighborhood Search is developed to solve the STPP-HVP. We address conflicts between the freight forwarder and shippers by setting the preferences of the freight forwarder and shippers as objectives and constraints, respectively. Objectives of the freight forwarder are to maximize the number of served requests and minimize the transport cost. Shippers' satisfaction is calculated by fuzzy set theory according to attribute values, and satisfaction values are limited to be higher or equal to a predefined value. In this way, the freight forwarder will try to find the solution with the lowest cost while ensuring service quality. Moreover, compared with using hard constraints, using fuzzy constraints gives more room to resolve conflicts between the freight forwarder and shippers. Compared with setting the objective as the sum of costs and dissatisfaction, the satisfaction values are higher when using fuzzy constraints. In the results, when the freight forwarder considers shippers' preferences that have conflicts with minimizing overall transport cost, the freight forwarder satisfies shippers with minimal cost by choosing more suitable modes and routes. The results also show that the proposed model improves shippers' satisfaction significantly by utilizing multiple transport modes and addresses conflicts between shippers by balancing the satisfaction levels.

Based on the experimental results, the following managerial insights are obtained:

1. In synchromodal transport planning, considering preferences is conducive to provide customized services by using the advantages of different modes. The shippers are more satisfied when their preferences are considered because corresponding attribute values are improved.
2. The conflicts between the freight forwarder and shippers are resolved by improving the service quality at the minimum cost. The transport reaches a trade-off between conflicting preferences of shippers by allocating appropriate services to specific requests without compromising any other's preferences.

In practice, freight forwarders in synchromodal transport can use the proposed model to improve their service quality and competitiveness by providing customer-oriented services. In the meantime, the cost, time, emissions, delay, and risk of damage could be reduced when considering related preferences using the proposed model. In this paper, we work with container shippers in the context of synchromodal transport. Nevertheless, the proposed methodologies are applicable in the case of other shippers as well if the importance of attributes is given. The proposed model can also be used to solve similar problems, such as pickup and delivery problems with transshipment and preferences, by simplifying the objectives and constraints related to multiple modes. However, there are some limits of the applicability of the proposed approach. The freight forwarder may also have different preferences on objectives, such as cost, time, and emissions, but the heterogeneous preferences of the freight forwarder are not taken into account in this model.

Future research can be conducted under the following directions:

1. When freight forwarders cannot satisfy shippers' preferences by themselves, they may want to collaborate. Future research can look into what is the most appropriate way to do the collaboration and (a) how multiple freight forwarders exchange requests from shippers? (b) how preferences are considered in collaborative planning? (c) what are the differences between transport plans with and without preferences in collaborative planning?
2. Shippers' stated preferences may be different from their actual behavior. To model shippers' preferences more accurately, future research should obtain revealed preferences by analyzing shippers' historical decisions and learning from shippers' current decisions in a dynamic setting.

Acknowledgments

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Appendix A. Evaluations on the performance of the ALNS

To evaluate the performance of the ALNS, we compared the proposed ALNS with an exact approach (Gurobi), as shown in Table 7. The exact approach does not consider preferences, i.e., Constraints (38)/(39) are removed, because considering fuzzy preferences will lead to computational burden and we would not be able to compare to the exact approach. In this case study, we use 116 services to serve one, three, or five requests. Because there are enough resources, all requests can be served when preferences are not considered. Therefore, we set that all requests need to be served by the exact approach, i.e., the objective function (1) is removed and Constraints (5) and (6) are replaced by:

$$\sum_{k\in K}\sum_{j\in N} y_{p(r)j}^{kr} = 1 \quad \forall r \in R \tag{50}$$

$$\sum_{k\in K}\sum_{j\in N} y_{jd(r)}^{kr} = 1 \quad \forall r \in R \tag{51}$$

As shown in Table 7, the ALNS without preferences obtains all optimal solutions found by the exact approach, but with a significantly less computation time. The exact approach needs more than 5 min to solve the instance with only one request and the computation time increases exponentially when the number of requests increases. When there are five requests, the time limit (3 h) is reached, but the exact approach still cannot guarantee the optimality of the found solution. In contrast, the ALNS only needs few seconds to find the (near) optimal solution under these instances. When considering preferences, such as fast transport, the ALNS can also find solutions that reduce transport time and improve satisfaction value.

Table 7
Comparison between results of the ALNS and the exact approach.

Case	R	N	Cost	Time	Reliability	Emissions	Risk	Barge	Train	Truck	S	F	t(s)
Gurobi	1	1	0.42	1.57	0	0.40	19	50.00	0.00	50.00	60	0	350.4
ALNS	1	1	0.42	1.57	0	0.40	19	50.00	0.00	50.00	60	0	0.1
ALNS⋆	1	1	0.72	0.54	0	0.89	0	0.00	0.00	100.00	79	1	1.1
Gurobi	3	3	0.38	1.63	0	0.37	39	60.00	0.00	40.00	55	0	5804.6
ALNS	3	3	0.38	1.63	0	0.37	39	60.00	0.00	40.00	55	0	0.9
ALNS⋆	3	3	0.72	0.56	0	0.89	0	0.00	0.00	100.00	81	3	6.0
Gurobi	5	5	0.41	1.53	0	0.33	39	57.14	14.29	28.57	60	1	10800.0∗
ALNS	5	5	0.41	1.53	0	0.33	39	57.14	14.29	28.57	60	1	2.1
ALNS⋆	5	5	0.64	0.53	0	0.77	0	0.00	20.00	80.00	79	5	7.1

⋆: The ALNS with preference (fast transport); R: number of requests; N: number of served requests; Cost: average cost of shipping one TEU one km; Time: average time ratio; Reliability: average delay ratio; Emissions: average CO_2 emissions per container per km; Risk: number of transshipments (TEU); Barge/Train/Truck: mode share of used barges/trains/trucks; S: average satisfaction value; F: number of requests which satisfy fuzzy constraints; t(s): computation time (s); ∗: time limit reached (3 h), and the optimality gap is 0.05%.

Appendix B. Re-planning approach and experiments

Synchromodal transport requires re-planning to handle uncertainty, such as the arrival of new demand and unexpected congestion. When re-optimizing previously taken decisions on modes and routes, the freight forwarder needs to consider different types of requests (potentially associated with different preferences for example due to newly received requests) at the same time and it becomes tricky to answer which container goes first or with which mode, as the trade-offs need to be taken care of. Therefore, the consideration of preferences comes down to the operational level with the concept of synchromodal transport.

The proposed model is extended to the re-planning with an event triggered approach, as shown in Algorithm 3.

Algorithm 3: Re-planning

Input: K, R, N, A; **Output:** X_{best};
set X_{current} as empty routes of K;
$X_{\text{best}} = ALNS(K, R, N, A, X_{\text{current}})$; // obtain the original solution.
for *time in time_horizon* **do**
  $X_{\text{current}} \leftarrow X_{\text{best}}$;
  if *unexpected events occur* **then**
    change the travel time τ_{ij}^{k} if delay occurs when vehicle k travel on link ij;
    define the set of requests influenced by delay and new requests as R_{new};
    remove requests that influenced by delay from X_{current}, and set this new current solution as X'_{current};
    $X_{\text{best}} = ALNS(K, R_{\text{new}}, N, A, X'_{\text{current}})$
  end
end
return X_{best};

To avoid a huge impact on other requests and reach the real-time requirement of synchromodal transport, only the influenced and new requests will be re-planned. The ALNS algorithm plans all requests only at the beginning of the planning horizon to obtain an original plan. When unexpected events occur, the influenced travel time and requests are updated, and the influenced requests are removed by a removal operator. In this case, the ALNS's initial solution is the current solution X'_{current} in Algorithm 3. If changes are announced after the pickup, the following constraints will be added in insertion operators to guarantee that request r is still transported by vehicle k:

$$\sum_{j \in N} y_{p(r)j}^{kr} = 1 \tag{52}$$

If request r has been transferred from vehicle k to l, transshipment terminal i needs to be unchanged:

$$s_{ir}^{kl} = 1 \tag{53}$$

$$\sum_{j \in N} y_{ij}^{lr} = 1 \tag{54}$$

The re-planning is illustrated by a simple but illustrative case in Fig. 12. In this case, three terminals, three services, and one request are considered. A truck fleet runs between terminals B and A with a speed of 75 km/h and the distance between B and A is 15 km. Between terminals A and C, both a train (speed: 45 km/h, capacity: 90 TEU) and a barge (speed: 15 km/h, capacity: 160 TEU) can be used to serve requests, and the distances for railway and waterway are 247.5 km and 262.5 km, respectively. The predefined departure/arrival times of the truck, barge, and train are 63h/63.35 h, 66h/83.5 h, 77h/82.5 h, respectively. Moreover, a request with a load of 12 TEU is considered. Its pickup terminal is B (pickup time is 63 h) and delivery terminal is C (due time is 85 h). The preference of the shipper is reliable transport.

Fig. 12(a) shows the original plan determined at time 0. At time 63.35 h, the request is transported by the truck fleet to terminal A and will wait for the barge. However, at time 65 h, the transport operator is notified that the water level in the waterway between

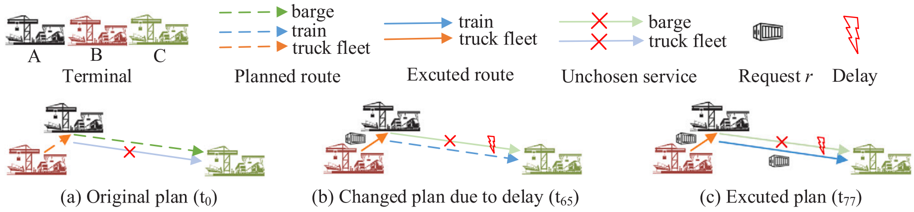

Fig. 12. Switching mode in re-planning.

Table 8
Re-planning under new requests.

Case	N	Cost	Time	Reliability	Emissions	Risk	Barge	Train	Truck	S
Original plan	20	0.61	0.64	0.65	0	45	0	45	55	82
New plan	25	0.64	0.60	0.69	0	45	0	37	63	81

N: number of served requests; Cost: average cost of shipping one TEU one km; Time: average time ratio; Reliability: average delay ratio; Emissions: average CO_2 emissions per container per km; Risk: number of transshipments (TEU); Barge/Train/Truck: mode share of used barges/trains/trucks; S: average satisfaction value.

Table 9
Linguistic terms and trapezoidal fuzzy numbers on attributes and satisfaction.

Linguistic terms	Fuzzy importance number $\tilde{w}'^j_i$	Linguistic terms	Fuzzy satisfaction number $\tilde{s}'^j_i$
Very low importance	[0, 0, 0.1, 0.3]	Very low satisfaction	[0, 0, 1, 3]
Low importance	[0.1, 0.3, 0.3, 0.5]	Low satisfaction	[1, 3, 3, 5]
Medium importance	[0.3, 0.5, 0.5, 0.7]	Medium satisfaction	[3, 5, 5, 7]
High importance	[0.5, 0.7, 0.7, 0.9]	High satisfaction	[5, 7, 7, 9]
Very high importance	[0.7, 0.9, 1.0, 1.0]	Very high satisfaction	[7, 9, 10, 10]

link AC is too low and the barge cannot deliver the request to terminal C before the due time. Then, the re-planning procedure is triggered, and the transport of this request is switched from the barge to train, as shown in Fig. 12(b). Between time 65 h and time 76 h, the containers are stored at terminal A and wait for the train. At time 76 h, the train arrives and starts to load this request. At time 77 h, the train finishes loading and departs from terminal A and will deliver the request at terminal C on time 82.5 h, which guarantees reliable transport as required by the shipper, as shown in Fig. 12(c).

We also designed a scenario with new requests, and the comparison between results before and after the re-planning is shown in Table 8. In this scenario, there are 20 original requests at time 0, and at time 40, five new requests are released. All these requests require fast transport. The new plan is obtained in three seconds by Algorithm 3. Table 8 shows that all new requests are served after the re-planning without changing plans of original requests. The shippers are also satisfied with the new plan because the attribute values match the requirements and the satisfaction value is stable after the re-planning.

Appendix C. Satisfaction calculation under relative preferences and experiments

When shippers express the relative importance of attributes, the linguistic terms represent relative preferences among attributes. In this case, the overall satisfaction value of all attributes S^r is:

$$S^r = Fuzzy'(f^r_1, f^r_2, f^r_3, f^r_4, f^r_5, \tilde{w}^r_1, \tilde{w}^r_2, \tilde{w}^r_3, \tilde{w}^r_4, \tilde{w}^r_5) \tag{55}$$

where $Fuzzy'()$ represents the MADM approach for relative preferences. The overall satisfaction value S^r is obtained according to the following steps.

Step 1: handle the shipper's vague preferences towards attributes. Five levels of linguistic terms are used to describe the importance of each attribute. Table 9 presents the attribute i's jth linguistics term l^j_i and the corresponding fuzzy importance number $\tilde{w}'^j_i$, where $\tilde{w}'^j_i = (a^j_i, b^j_i, c^j_i, d^j_i)$, $1 \le j \le 5$. The membership grades $\mu(x)$ are represented by real number ranging from [0,1]. For request r and attribute i, the fuzzy importance number $\tilde{w}^r_i$ is obtained based on the linguistic preference expressed by the shipper.

Step 2: obtain the actual attribute value's level. According to the actual attribute value f^r_i, the jth level's fuzzy satisfaction number $\tilde{s}'^j_i$ is given, where $\tilde{s}'^j_i = (\omega^j_i, \beta^j_i, \sigma^j_i, \theta^j_i)$, $1 \le j \le 5$. When the attribute value f^r_i is less than the expected value, it meets the relevant satisfaction level, and the actual level $\tilde{s}^r_i$ is the highest level reached. The membership grades $\mu(x)$ are represented by real numbers ranging from [0,10]. Table 9 also shows the linguistic terms for satisfaction and their corresponding fuzzy number.

Step 3: link the preference, attribute value, and satisfaction. After Steps 1 and 2, the fuzzy importance number $\tilde{w}^r_i$ and the actual satisfaction level $\tilde{s}^r_i$ for request r and attribute i are obtained. Using these fuzzy numbers, the fuzzy evaluation matrix can be constructed:

$$S^r = \tilde{w}^r_1 \otimes \tilde{s}^r_1 \oplus \tilde{w}^r_2 \otimes \tilde{s}^r_2 \oplus \tilde{w}^r_3 \otimes \tilde{s}^r_3 \oplus \tilde{w}^r_4 \otimes \tilde{s}^r_4 \oplus \tilde{w}^r_5 \otimes \tilde{s}^r_5 \oslash (\tilde{w}^r_1 \oplus \tilde{w}^r_2 \oplus \tilde{w}^r_3 \oplus \tilde{w}^r_4 \oplus \tilde{w}^r_5) = (z_1, z_2, z_3, z_4) \tag{56}$$

Table 10
Expected values of each attribute.

Linguistic terms	Expected value				
of satisfaction	Cost	Time	Reliability	Emissions	Risk of damage
Very high	[0, 0.8]	[0, 0.8]	[0, 0.05]	[0, 0.5]	[0, 10]
High	(0.8, 1.2]	(0.8, 1.2]	(0.05, 0.1]	(0.5, 0.9]	(10, 20]
Medium	(1.2, 1.6]	(1.2, 1.6]	(0.1, 0.15]	(0.9, 1.3]	(20, 30]
Low	(1.6, 2.0]	(1.6, 2.0]	(0.15, 0.20]	(1.3, 1.7]	(30, 40]
Very low	(2.0, +∞]	(2.0, +∞]	(0.20, +∞]	(1.7, +∞]	(40, +∞]

Table 11
Experiment results under relative preferences (100 requests).

Scenario	R	#r	S	Total cost	Cost	Time	Reliability	Emission	Risk	t(s)
benchmark	100	100	–	196130.69	0.51	1.51	0	0.35	1.59	–
A-1	100	82	9.60 (6.77∗)	174637.14	0.46	1.38	0	0.34	1.09	1333.15
A-2	100	66	9.93 (5.96∗)	168207.16	0.70	0.62	0	0.59	0.76	4098.90
A-3	100	100	9.43 (9.43∗)	196130.69	0.51	1.51	0	0.35	1.59	3582.21
A-4	100	100	9.38 (8.20∗)	196299.25	0.50	1.41	0	0.38	0.1	4740.46
A-5	100	89	9.38 (6.84∗)	181896.14	0.45	1.66	0	0.28	1.89	240.62
B-1	100	95	9.38 (7.62∗)	198095.42	0.52	1.55	0	0.33	2.14	280.98
B-2	100	98	9.43 (7.38∗)	198090.03	0.54	1.45	0	0.38	1.49	412.35
B-3	100	98	9.49 (7.69∗)	209791.81	0.54	1.23	0	0.40	1.77	473.68

R: number of total requests; #r: number of served requests; S: satisfaction value; Cost: unit cost(/km/TEU); Time: time ratio (%); Reliability: delay ratio (%); Emission: unit emission cost (/km/TEU); Risk: number of transferred containers (TEU); t(s): computation time (seconds). The value with ∗ means satisfaction of the benchmark when considering relevant preferences.

The operations $\otimes$, $\oplus$, and $\varnothing$ are defined by Chen and Niou (2011). Let $\tilde{u} = (u_1, u_2, u_3, u_4)$ and $\tilde{v} = (v_1, v_2, v_3, v_4)$ be two trapezoidal fuzzy number, where $0 \le u_1 \le u_2 \le u_3 \le u_4$ and $0 \le v_1 \le v_2 \le v_3 \le v_4$. The operations between $\tilde{u}$ and $\tilde{v}$ are defined as:

$$\tilde{u} \oplus \tilde{v} = (u_1 + v_1, u_2 + v_2, u_3 + v_3, u_4 + v_4) \tag{57}$$

$$\tilde{u} \otimes \tilde{v} = (u_1 \times v_1, u_2 \times v_2, u_3 \times v_3, u_4 \times v_4) \tag{58}$$

$$\tilde{u} \varnothing \tilde{v} = (\frac{u_1}{v_4}, \frac{u_2}{v_3}, \frac{u_3}{v_2}, \frac{u_4}{v_1}) \tag{59}$$

Step 4: calculate the satisfaction value by defuzzification. The satisfaction value S^r is calculated by defuzzifying (z_1, z_2, z_3, z_4):

$$S^r = (z_1, z_2, z_3, z_4) = \frac{z_1 + z_2 + z_3 + z_4}{4} \tag{60}$$

Based on the studied transport network, the expected value of each linguistic term of satisfaction is given in Table 10.

Similar to Section 6, scenarios for shippers with homogeneous and heterogeneous preferences are designed. In the homogeneous preferences scenario (A), five sub-scenarios, i.e., the most important attribute is Cost (A-1), Time (A-2), Reliability (A-3), Risk of damage (A-4), and Emissions (A-5), are considered. For the heterogeneous preferences scenario (B), different preferences will be assigned to each request randomly. For the three sub-scenarios with heterogeneous preferences (B-1, B-2 & B-3), the preference proportions of five attributes, i.e., [Cost, Time. Reliability, Risk of damage, and Sustainability], are [30, 0, 20, 10, 40], [20, 20, 10, 30, 20], and [30, 40, 10, 10, 10] for cases B-1, B-2, B-3, respectively. For the ease of writing, in this section, we use a similar expression with Section 6, e.g., "low-cost preference" means "the most important attribute is Cost". Since the proportion of served requests is not high in some cases in Section 6, this section tries a setting with more flexibility, i.e., barges and trucks with flexible services, and trains with fixed services. The flexible services mean flexible routes and schedules, i.e., Constraints (20) and (32) are not applied.

Results with an instance with 100 requests are shown in Table 11. The satisfaction and attribute values are improved by incorporating preferences. In the low-cost transport (A-1), the unit cost reduces by 10% from 0.51 to 0.46. In the fast transport scenario (A-2), the reduction of time ratio is 59%. Risk of damage increases in the low-emission transport scenario (A-5) because more sustainable transport modes are selected and more transshipments are needed. As for scenario B, because of the heterogeneous preferences of shippers, the improvement on certain attributes is not significant. Mode shares of the barge, train, and truck are presented in Fig. 13. In the homogeneous preferences scenario, the usage of vehicles can reflect their corresponding preferences. In low-cost, reliable and low-emissions transport cases, truck shares a low percentage compared with other two modes. In the fast transport case, the barge is not the preferred mode. For the heterogeneous preferences scenario, the mode shares vary among cases.

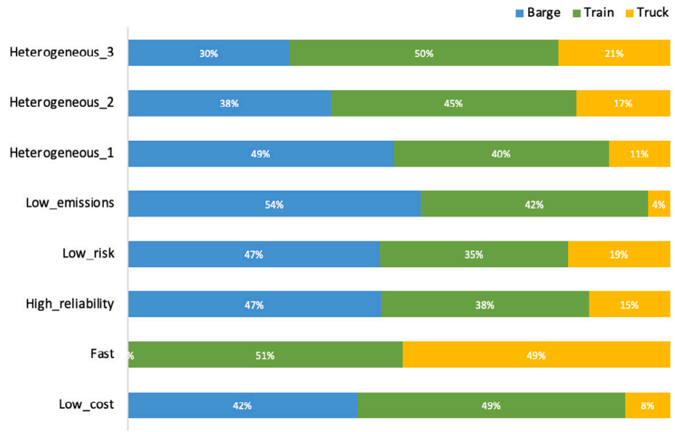

Fig. 13. Mode share under relative preferences (100 requests).

References

Afshar-Bakeshloo, M., Mehrabi, A., Safari, H., Maleki, M., Jolai, F., 2016. A green vehicle routing problem with customer satisfaction criteria. J. Ind. Eng. Int. 12 (4), 529–544.

Aksen, D., Kaya, O., Salman, F.S., Tüncel, Ö., 2014. An adaptive large neighborhood search algorithm for a selective and periodic inventory routing problem. European J. Oper. Res. 239 (2), 413–426.

Arunotayanun, K., Polak, J.W., 2011. Taste heterogeneity and market segmentation in freight shippers' mode choice behaviour. Transp. Res. E Logist. Transp. Rev. 47 (2), 138–148.

Baniamerian, A., Bashiri, M., Zabihi, F., 2018. Two phase genetic algorithm for vehicle routing and scheduling problem with cross-docking and time windows considering customer satisfaction. J. Ind. Eng. Int. 14 (1), 15–30.

Baykasoğlu, A., Subulan, K., 2016. A multi-objective sustainable load planning model for intermodal transportation networks with a real-life application. Transp. Res. E Logist. Transp. Rev. 95, 207–247.

Behdani, B., Fan, Y., Wiegmans, B., Zuidwijk, R., 2014. In: Behdani, B., Fan, Y., Wiegmans, B., Zuidwijk (Eds.), Multimodal Schedule Design for Synchromodal Freight Transport Systems. pp. 424–444.

Chen, S.-J., Hwang, C.-L., 1992. Fuzzy multiple attribute decision making methods. In: Fuzzy Multiple Attribute Decision Making. Vol. 1992. Springer, pp. 289–486.

Chen, S.-M., Niou, S.-J., 2011. Fuzzy multiple attributes group decision-making based on fuzzy preference relations. Expert Syst. Appl. 38 (4), 3865–3872.

Cheng, Q., Wang, C., 2021. Container liner shipping network design with shipper's dual preference. Comput. Oper. Res. 128, 105187.

Dayarian, I., Crainic, T.G., Gendreau, M., Rei, W., 2016. An adaptive large-neighborhood search heuristic for a multi-period vehicle routing problem. Transp. Res. E Logist. Transp. Rev. 95, 95–123.

de Sá, E.M., Contreras, I., Cordeau, J.-F., 2015. Exact and heuristic algorithms for the design of hub networks with multiple lines. European J. Oper. Res. 246 (1), 186–198.

Delbart, T., Molenbruch, Y., Braekers, K., Caris, A., 2021. Uncertainty in intermodal and synchromodal transport: review and future research directions. Sustainability 13 (7), 3980.

Demir, E., Burgholzer, W., Hrušovskỳ, M., Arıkan, E., Jammernegg, W., Van Woensel, T., 2016. A green intermodal service network design problem with travel time uncertainty. Transp. Res. B 93, 789–807.

Duan, L., Tavasszy, L.A., Rezaei, J., 2019. Freight service network design with heterogeneous preferences for transport time and reliability. Transp. Res. E Logist. Transp. Rev. 124, 1–12.

Dumez, D., Lehuédé, F., Péton, O., 2021. A large neighborhood search approach to the vehicle routing problem with delivery options. Transp. Res. B 144, 103–132.

Ghannadpour, S.F., Noori, S., Tavakkoli-Moghaddam, R., Ghoseiri, K., 2014. A multi-objective dynamic vehicle routing problem with fuzzy time windows: Model, solution and application. Appl. Soft Comput. 14, 504–527.

Giusti, R., Manerba, D., Bruno, G., Tadei, R., 2019. Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues. Transp. Res. E Logist. Transp. Rev. 129, 92–110.

Grangier, P., Gendreau, M., Lehuédé, F., Rousseau, L.-M., 2016. An adaptive large neighborhood search for the two-echelon multiple-trip vehicle routing problem with satellite synchronization. European J. Oper. Res. 254 (1), 80–91.

Guo, W., Atasoy, B., Beelaerts van Blokland, W.W.A., Negenborn, R.R., 2020. A dynamic shipment matching problem in hinterland synchromodal transportation. Decis. Support Syst. 134, 113289.

Jiang, X., Mao, H., Wang, Y., Zhang, H., 2020. Liner shipping schedule design for near-sea routes considering big customers' preferences on ship arrival time. Sustainability 12 (18), 7828.

Kahraman, C., 2008. Fuzzy Multi-Criteria Decision Making: Theory and Applications with Recent Developments. Vol. 16. Springer Science & Business Media.

Kallas, S., 2011. Transport 2050: Comission Outlines Ambitious Plan to Increase Mobility and Reduce Emmisions. Technical Report, Technical Report March.

Khakdaman, M., Rezaei, J., Tavasszy, L.A., 2020. Shippers' willingness to delegate modal control in freight transportation. Transp. Res. E Logist. Transp. Rev. 141, 102027.

Kurtuluş, E., Çetin, İ.B., 2020. Analysis of modal shift potential towards intermodal transportation in short-distance inland container transport. Transp. Policy 89, 24–37.

Los, J., Spaan, M.T., Negenborn, R.R., 2018. Fleet management for pickup and delivery problems with multiple locations and preferences. In: International Conference on Dynamics in Logistics. Springer, pp. 86–94.

Masson, R., Lehuédé, F., Péton, O., 2013. An adaptive large neighborhood search for the pickup and delivery problem with transfers. Transp. Sci. 47 (3), 344–355.

Öncan, T., Altınel, İ.K., Laporte, G., 2009. A comparative analysis of several asymmetric traveling salesman problem formulations. Comput. Oper. Res. 36 (3), 637–654.

Qu, Y., Bard, J.F., 2012. A GRASP with adaptive large neighborhood search for pickup and delivery problems with transshipment. Comput. Oper. Res. 39 (10), 2439–2456.

Ramos, C., Burges, A., van der Geest, W., Hendriks, I., van Hassel, E., Shobayo, P., Samuel, L., Atasoy, B., van Dorsser, C., Bijlsma, R., Macquart, A., Pedersen, J., Eiten, J., Grunder, D., Alias, C., 2020. D.2.1: Detailed Requirements of the NOVIMOVE Transport Model. Technical Report.

Ropke, S., Pisinger, D., 2006. An adaptive large neighborhood search heuristic for the pickup and delivery problem with time windows. Transp. Sci. 40 (4), 455–472.

Shao, C., Wang, H., Yu, M., 2022. Multi-objective optimization of customer-centered intermodal freight routing problem based on the combination of DRSA and NSGA-III. Sustainability 14 (5), 2985.

State Council of China, 2021. Action plan for carbon dioxide peaking before 2030. Online. http://english.www.gov.cn/policies/latestreleases/202110/27/content_WS6178a47ec6d0df57f98e3dfb.html. (Accessed 27 October 2021).

SteadieSeifi, M., Dellaert, N.P., Nuijten, W., Van Woensel, T., Raoufi, R., 2014. Multimodal freight transportation planning: A literature review. European J. Oper. Res. 233 (1), 1–15.

Tavasszy, L., Behdani, B., Konings, R., 2017. Intermodality and synchromodality. In: Ports and Networks. Routledge, pp. 251–266.

Van Leekwijck, W., Kerre, E.E., 1999. Defuzzification: criteria and classification. Fuzzy Sets and Systems 108 (2), 159–178.

Zhang, Y., Atasoy, B., Negenborn, R.R., 2022a. Preference-based multi-objective optimization for synchromodal transport using adaptive large neighborhood search. Transp. Res. Rec. 2676 (3), 71–87.

Zhang, Y., Guo, W., Negenborn, R.R., Atasoy, B., 2022b. Synchromodal transport planning with flexible services: Mathematical model and heuristic algorithm. Transp. Res. C 140, 103711.

Zhang, J., Lam, W.H., Chen, B.Y., 2013. A stochastic vehicle routing problem with travel time uncertainty: trade-off between cost and customer service. Netw. Spat. Econ. 13 (4), 471–496.

Zhang, W., Wang, X., Yang, K., 2020a. Uncertain multi-objective optimization for the water–rail–road intermodal transport system with consideration of hub operation process using a memetic algorithm. Soft Comput. 24 (5), 3695–3709.

Zhang, Z., Zhang, D., Tavasszy, L.A., Li, Q., 2020b. Multicriteria intermodal freight network optimal problem with heterogeneous preferences under belt and road initiative. Sustainability 12 (24), 10265.