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A real-time synchromodal framework with co-planning for routing of containers and vehicles[☆]

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ABSTRACT

This paper considers a decentralized container transport system in which two decision-makers are involved in getting a container from its origin to its destination: a logistics service provider (LSP) and a flexible service operator (FSO). While the LSP receives shipment requests from shippers and controls the movement of containers over a multimodal network by booking scheduled (e.g., barges and trains) and flexible services (e.g., trucks) from service operators, the FSO manages a fleet of vehicles (e.g., trucks) that have flexible routes and departure times to fulfill the transport requests proposed by the LSP. In the literature, most of the studies focus on either container routing, by assuming all services have fixed routes and trucks are unlimited, or vehicle routing in a road network. This paper investigates the integrated problems of routing containers and vehicles through a multimodal network from a decentralized perspective considering the decision authorities of the LSP and the FSO. A *synchromodal* framework is designed to control the decision process which enables to utilize the benefits of real-time mode and route changes. To investigate the impact of communication, we develop a *co-planning* method under the synchromodal framework to coordinate the transport plans between the LSP and the FSO in real-time. The co-planning method considers a realistic level of information exchange and adheres to no changes in their responsibilities and authorities compared to current practice. The performance of the co-planning method is evaluated under various scenarios. The experimental results show that co-planning, using expected transport request fulfillment as feedback, reduces the total costs of container transportation and decreases the distance traveled by flexible vehicles under most of the scenarios.

1. Introduction

Hinterland container transportation is the movement of containers between deep-sea ports and inland terminals by using barges, trains, trucks, or any combination of them (Guo et al., 2020). With the increasing volume of global trade and the trend towards larger ships, efficient hinterland transportation becomes increasingly important for reducing traffic congestion, transport costs, empty travels, delays, and emissions. In 2021, global containerized trade reached 171.1 million twenty-foot equivalent units (TEUs), and the volume is projected to keep increasing with the global economy recovery (GTAS, 2022). At the same time, greenhouse emissions from transportation reached 729 million tons in Europe while road transport occupied 72% thereof (EEA, 2022). Compared with trucks, barges and trains generate lower costs and emissions but have longer travel times and less flexibility (Zhang et al., 2022). As

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an alternative, intermodal transportation has been proposed to provide efficient and sustainable services by using different transport modes and combining them in a multimodal network (Demir et al., 2016).

In intermodal transport, multiple stakeholders are involved in getting a container from its origin to its destination, including shippers, a logistics service provider, terminal operators, scheduled and flexible service operators (Crainic et al., 2018). Shippers are the entities that propose shipment requests for their container loads. Logistics service provider (LSP) controls the movement of containers over a multimodal network by booking capacities from terminal and service operators. Terminal operators manage the loading, unloading, and storage operations at terminals. Scheduled service operator (SSO) provides transport capacities of time-scheduled and route-fixed services (e.g., barges and trains). Flexible service operator (FSO) decides the departure times and routes of flexible vehicles (e.g., trucks) to fulfill the transport requests proposed by the LSP. At the operational level, two key decisions need to be made: the mode and route choices for container transportation, and the route and departure times of flexible vehicles.

In the literature, container transportation and vehicle routing have usually been investigated independently. Container routing decisions over a multimodal network are often taken assuming that the number of trucks is infinite (Steadieseifi et al., 2014). This is an unreasonable assumption since in busy port areas, according to practitioners, it can easily take two hours before a vacant truck is available on site. If the decline in truck driver professionals continues (IRU, 2021), the availability of ad-hoc trucks will decrease further. Integrating container and vehicle routing decisions is expected to improve the efficiency of transport plans and the utilization rate of the fleet significantly. However, only a few studies considered the problem of routing containers and vehicles integrally in a multimodal network (e.g., Larsen et al., 2021a; Müller et al., 2021; Zhang et al., 2022), and all these studies consider a centralized decision-maker. In practice, most container transport systems are controlled by multiple stakeholders who prefer to share limited information with each other and keep their own decision authority (Lee and Song, 2017).

In this paper, we consider a decentralized container transport system with two decision-makers: the LSP that decides the mode and route choices of shipment requests over a multimodal network, and the FSO that decides vehicle routes to fulfill the transport requests proposed by the LSP, as shown in Fig. 1. Each shipment request is characterized by its origin, destination, announce time (the time when it arrives in the system), release time (the time when it is ready to start transportation), due time, container volume, and delay cost (delay is allowed but with a penalty). Each scheduled service is characterized by its mode, origin, destination, capacity, departure time, arrival time, and transport cost. Each flexible service is defined by its origin, destination, estimated transport time and cost. At the beginning of a given planning horizon, the LSP receives weekly scheduled services from the SSO with fixed time schedules and receives flexible services from the FSO with estimated transport times. At each decision time, the LSP decides the modes and routes for the newly received shipment requests and sends transport requests to the FSO if flexible services are selected. The transport request might have the same origin–destination as the original shipment request, but it could also be part of the whole journey. For example, the transport plan for a shipment request is to be transported from its origin A to terminal B by truck, and from terminal B to its destination C by barge. Then the transport request is to transport the same amount of containers from terminal A to B. The FSO controls the movement of vehicles to fulfill the transport requests proposed by the LSP. Due to the limitation of trucks and the dynamics in demand, the transport request might need to wait at terminals until a vehicle is available, the arrival times of transport requests are thus uncertain. Thanks to the development of information technologies, the real-time position of containers is available to the LSP and the real-time position of flexible vehicles is available to the FSO. Under the intermodal paradigm, the mode and route choices of shipment requests are not allowed to be changed even when infeasible transshipments happen. Increasing the flexibility and responsiveness of transport plans is expected to increase operational efficiency and reduce its environmental impact.

Synchromodal transport is a paradigm that seeks to achieve flexible and responsive transport systems, mainly by allowing the LSP to change container routes and mode choice dynamically, even after departure, without waiting for a response from the shippers (Reis, 2015). This way, the LSP can use the available capacity better and adapt plans if disruptions or disturbances occur. Besides, the real-time aspect of synchromodal transport clearly sets it apart from intermodal transport at the operational level. Real-time mode changes performed by the LSP can not only improve efficiency by making rail and water modes more attractive but can also improve the performance of the transport system by changing modes and routes depending on the available capacity of each service (van Riessen et al., 2016).

Thanks to the development of communication technologies, stakeholders are able to communicate with each other in real-time. The efficiency of the transport system is expected to benefit from close cooperation between the stakeholders. However, very little research has been done on cooperation methods in synchromodal transport systems. Co-planning is a cooperation method that aims at improving the common operation of a transport system by exchanging consciously chosen, realistic information and keeping the responsibilities within each autonomous, cooperating party as much as possible. The responsibility of each organization is realistic and clear, and the information exchange is limited to potential schedules and aggregated costs.

Co-planning is a necessary concept as it distinguishes research that emphasizes realistic assumptions on how entities cooperate. In this paper, we propose a co-planning method under the synchromodal paradigm that entails communication between the LSP and the FSO. The cooperation relies on automated communication of transport requests' estimated arrival times similar to what is being communicated manually in current practice. The LSP thus updates transport plans based on the estimation by setting departure time lower bounds. For example, if the FSO informs the LSP that the transport request might arrive at a time that is too late to transfer to another mode, then LSP could change the mode and route choice for the original shipment request to avoid infeasible transshipment.

When heterogeneous freight transport partners cooperate, each partner has a different focus and priorities and is thus likely to apply different planning methods to suit their decision types better. Very little research has been conducted in the area of freight transport with interfaces between different methods. Rivera and Mes (2019) integrate the long-haul with the drayage operations and study the interface between these two. They consider both decisions taken by the same entity, but the long-haul is modeled

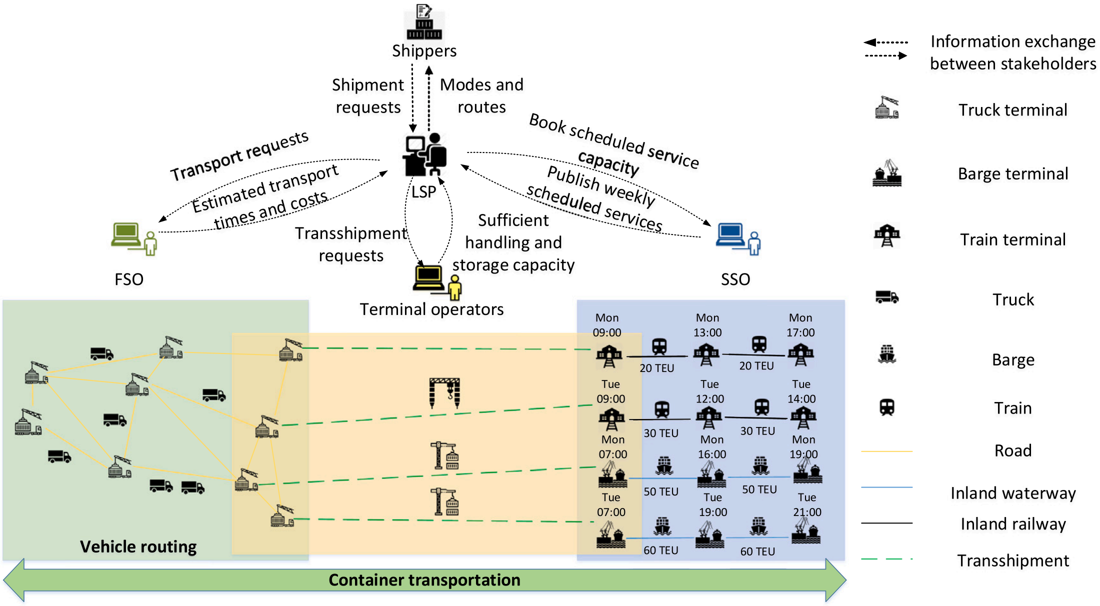

Fig. 1. Integrated routing of containers and vehicles in a decentralized multimodal transport system.

as a Markov decision process model and the drayage as a mixed integer linear programming model. Interfaces between different methods will influence the performance of any system and must therefore be taken into account.

In this paper, the LSP's optimization is developed by enhancing the mixed integer linear programming (MILP) model published in Guo et al. (2020), and the FSO's optimization is developed based on the model predictive control (MPC) method published in Larsen et al. (2021a). In MILP, binary variables are designed to describe the assignments of shipment requests to scheduled and flexible services; in MPC, continuous variables are designed to describe the container flows on arcs at different time steps. Therefore, the transport requests proposed by the LSP must be transited into aggregated container demand, and the container flow decisions decided by the FSO must be transited back to the requests' assignments. Different from Guo et al. (2020), the LSP's real-time optimization in this paper is extended to reconsider plans periodically before and during the transportation and incorporate expected transport requests' arrival times communicated by the FSO. Different from Larsen et al. (2021a), the model of the FSO distinguishes containers from different transport requests in bundles and has a mechanism that encourages the FSO to start transports early for urgent requests.

The main contributions of this paper are briefly summarized as follows. First, we introduce the problem of integrating the routing of containers and vehicles through a multimodal network from a decentralized perspective considering the decision authorities of the LSP and the FSO. Second, we develop a synchromodal framework to improve the efficiency of transport plans by dynamically updating mode and route choices for shipment requests. Third, we develop a co-planning method under the synchromodal framework to investigate the benefits of a realistic level of communication. Fourth, we develop different modeling methods for the LSP and the FSO and design transition procedures to synchronize different decision types. Fifth, we design multiple scenarios to evaluate the proposed approaches and provide insights about their added value.

In the remainder of this paper, Section 2 briefly reviews the related works. The problem is formally described in Section 3. In Section 4, we discuss the differences between synchromodal transport with co-planning and intermodal transport paradigm. In Section 5 the mathematical formulation of the proposed method is detailed and in Section 6 numerical experiments comparing the performance of synchromodal with co-planning and intermodal planning without cooperation are shown. The managerial implications are summarized in Section 7. Conclusions and outlooks on future research are drawn in Section 8.

2. Related works

Over the past decades, different freight transport paradigms have emerged in the literature and in the industry: multimodal, intermodal, co-modal, and more recently, synchromodal transportation (Ambra et al., 2018). Multimodal transportation is defined as the transportation of goods by a sequence of at least two different modalities (Steadieseifi et al., 2014; Archetti et al., 2022). Intermodal transportation refers to a particular type of multimodal transportation that uses the same loading units (e.g., a container) from the origin to the destination of a shipment (Crainic et al., 2018). Co-modal transportation focuses on the efficient and sustainable utilization of different modes on their own and in combination (Steadieseifi et al., 2014). As a further evolution of these paradigms, synchromodal transportation emphasizes flexibility in the dynamic updating of transport plans by using real-time information regarding the status of the transport system (Giusti et al., 2019; Pfoser et al., 2022).

2.1. Optimization models for synchromodal transport systems

To fully use the flexibility that synchromodal transport offers via real-time mode and route changes, optimization models in synchromodal transport planning need to differ from those applied to other paradigms (e.g., intermodal transport). In the literature, transport optimization models are often classified as strategic, tactical, or operational planning. While strategic and tactical planning focus on network and service design in long and medium time horizons, operational planning deals with the routing of containers and/or vehicles in short time horizons.

In the literature, only a few studies research strategic/tactical planning for synchromodal transport systems. Riessen et al. (2020) develop a method for a cargo fare class mix problem to balance revenue maximization and capacity utilization in a synchromodal container transport network. Giusti et al. (2020) propose a two-stage stochastic programming model with recourse for a multi-period transshipment location–allocation problem with flow synchronization under stochastic handling operations. Giusti et al. (2021) introduce the concept of smart steaming in the paradigm of synchromodality for the real-time adjustment of travel speeds to pursue overall efficiency and sustainability. Bilegan et al. (2022) propose a scheduled service network design model with revenue management consideration for intermodal consolidation-based freight transport carriers. Taherkhani et al. (2022) investigate a tactical planning problem of an integrated multi-modal multi-stakeholder system in which revenue management concepts including shipper categories, demand classification, penalty costs, and service bundles are addressed. Giusti et al. (2023) develop a mixed integer linear programming model for the synchronized multi-commodity multi-service transshipment-hub location problem faced by a logistics service provider in the context of synchromodal logistics.

Most of the studies in synchromodal transportation lie in the field of operational planning. These existing models can be further divided into two groups: container routing and shipment matching. While container routing models focus on the flow of containers on multimodal networks (e.g., Li et al. (2015), Qu et al. (2019), Yee et al. (2021), Larsen et al. (2021a), Rivera and Mes (2022) and Akyüz et al. (2023)), shipment matching models design binary variables to assign a shipment request (i.e, a bundle of containers with the same attributes) with specific time windows to multimodal services with specific time schedules (e.g., Demir et al. (2016), Guo et al. (2020), Müller et al. (2021) and Zhang et al. (2022)). Besides, most of the above studies consider vehicles having flexible departure times (e.g., Qu et al. (2019) and Guo et al. (2020)), and only a few consider the routing of containers and vehicles integrally in a multimodal network. Larsen et al. (2021a) develop a model predictive controller to determine which combination of trucks, trains, and barges to use for transporting containers and which routes trucks should use as one integrated problem. They prove that routing containers and trucks simultaneously can improve truck utilization. Müller et al. (2021) present a mixed integer linear programming model for integrating vehicle routing into an intermodal service network design problem. The integrated model is proved to have better performance on cost reductions than a successive planning approach. Zhang et al. (2022) develop a mixed integer linear programming model to plan vehicle and container routes simultaneously. They demonstrate that the proposed model can reduce operational costs by 14% on average when using flexible vehicles.

2.2. Cooperation methods for decentralized synchromodal transport systems

The optimization models published in synchromodal transport mainly assume one decision maker has access to all information and authority to make all decisions. However, in practice, a multimodal transport system often involves multiple actors that control different types of resources. These actors prefer to share limited information with each other and keep their own decision authority. The efficiency of the transport system is thus highly dependent on how well the involved actors cooperate. The methods for cooperation among multiple decision-makers in synchromodal transportation can be divided into three groups: decentralized planning, distributed planning, and co-planning. In decentralized planning, there is no cooperation and no information sharing between the participating actors. Each actor is responsible only for their own operations. In distributed planning, there is always information exchanged and the responsibility is shared, partially or fully. Li et al. (2017) use distributed optimization methods to facilitate cooperation on the routing of containers between multiple transport operators. Each operator has a unique network that does not overlap with the others. The information exchanged between the operators is symmetric and the responsibilities of each organization are similar. However, in a competitive environment, the actors will often be reluctant to join collaborations where they have to share sensitive information and hand over responsibility and decision-power over core decisions. Instead, they are only interested in a realistic level of information sharing, which is defined as co-planning. Larsen et al. (2021b) introduce a co-planning method to let a transport provider with only trucks in its vehicle fleet influence the departure time of a barge that belongs to a different operator.

2.3. Dynamic frameworks for synchromodal transport systems

In synchromodal transportation, dynamic updating of transport plans based on real-time information plays a key role in differentiating synchromodality from other paradigms. In Ambra et al. (2019) multi-agent simulations show that dynamic synchromodal solutions perform better than intermodal ones when the transport system is subject to uncertainty. Some works focus on robust plans with the assumption that the uncertain parameter follows a given probability (e.g., Demir et al. (2016) and Dong et al. (2015)), while others rely on replanning (e.g., Qu et al. (2019), Guo et al. (2020) and Larsen et al. (2021a)). Many only replan when a disturbance makes the current plan infeasible, a few systematically replan at fixed time points (Akyüz et al., 2023). Replanning when a plan becomes infeasible (van Riessen et al., 2016) and possibly only replan for parts of the transport system (Guo et al., 2021) can reduce computational complexity significantly. This will create faster responses. On the other hand, replanning all decisions at regular time points promises better possible plans for all parts of the system. The advantage of using regular decision times is that the time available for computing the plan is known. This is especially an advantage if new information is available frequently and irregularly.

2.4. Summary

Based on the above review of previous works, this study focuses on the real-time synchromodal framework with co-planning for integrated routing of containers and vehicles. While most of the studies assume a centralized decision-maker, this paper considers different decision-makers responsible for the routing of containers and vehicles independently. Synchromodal frameworks that allow real-time changes of modes and routes are designed for a decentralized container transport system. Furthermore, the communication mechanism under the co-planning method distinguishes this paper from the previous work on cooperative planning.

3. Problem description

In multimodal transport networks, different stakeholders are in control of different parts of the infrastructure and resources needed to move containers making access to available information limited. The scarcity of resources is important to take into account when planning transport operations. When a container's departure is decided immediately before it is to be loaded into a vehicle, knowing the availability of that vehicle becomes crucial for the feasibility and efficiency of the transport plans. In this paper, we study the problem of integrated routing of containers and vehicles in a decentralized environment where there is no centralized coordination between stakeholders. The main stakeholders involved in container transportation include shippers, terminal operators, the scheduled service operator (SSO), the flexible service operator (FSO), and the logistics service provider (LSP). A full table of notation can be found in Appendix.

Shippers (e.g., manufacturers and freight forwarders) generate container transport demand and send shipment requests to the LSP. Let R be the set of shipment requests received over a given planning horizon T. Each shipment request $r \in R$ is characterized by its announce time t_r^{announce} (i.e., the time when the LSP receives the request), release time t_r^{release} (i.e., the time when the shipment is available for transportation) at origin terminal o_r, due time t_r^{due} (i.e., the time that the shipment needs to be delivered) at destination terminal d_r, and container volume q_r (i.e., the number of containers). All shipment requests must be fulfilled eventually; delay in delivery is allowed but with a delay cost coefficient per container per hour overdue c_r^{delay}. The lead time of shipment request r is represented as, $LD_r = t_r^{\text{due}} - t_r^{\text{release}}$. All containers are standard 40ft. All shipment requests are flexible (i.e., shippers let the LSP change mode and route choices before and during transport) and splittable (i.e., shipments might be delivered in multiple bundles).

Terminal Operators handle transshipment operations at terminals by providing sufficient loading, unloading, and storage capacities to the LSP. Let N be the set of terminals.

SSO publishes weekly scheduled services (e.g., barges and trains) to the LSP at the beginning of the planning horizon. Let $S^{\text{scheduled}}$ be the set of scheduled services that have limited capacities and fixed time schedules but can help generate economies of scale. Each scheduled service $s \in S^{\text{scheduled}}$ is characterized by its origin terminal o_s, destination terminal d_s, free capacity in container slots Q_s, departure time (i.e., the time before loading operation) TD_s, arrival time (i.e., the time after unloading operation) TA_s, transport cost c_s. The SSO allows the LSP to book the scheduled capacities at the last minute before service departure.

FSO [Decision maker] provides flexible services (e.g., trucks) to the LSP. Let S^{flexible} be the set of flexible services. Each flexible service $s \in S^{\text{flexible}}$ is characterized by its origin terminal o_s, destination terminal d_s, estimated transport time t_s and cost c_s. The FSO manages a fleet of vehicles to fulfill the transport requests proposed by the LSP. There are no time and location restrictions for the vehicles, i.e., vehicle routes can be infinite in time and do not have to end in specific locations. The FSO routes the vehicles in their fleet and decides where and when to load and unload containers, they furthermore decide how many containers from each transport request to transport. The FSO may store containers at intermediate stacks if it is beneficial. Let γ be the fleet size. Let τ_{ij} be the travel time from terminal i to terminal j. Travel times are assumed to include loading and unloading. Let ω_{ij} be the cost of driving a flexible vehicle from terminal i to j, the cost of driving is the same when empty and full.

LSP [Decision maker] receives real-time shipment requests from shippers and receives weekly scheduled services from the SSO and flexible services from the FSO and sufficient handling capacities from terminal operators. The LSP decides the mode and route choices for the shipment requests by selecting one service or multiple services, such as transporting a shipment from its origin to a transfer terminal by a truck service and from the transfer terminal to its destination by a barge service. If a scheduled service is selected, the LSP books scheduled capacities from the SSO; if a flexible service is selected, the LSP sends the transport request r' to the FSO, which consists of a pick-up time $t_{r'}^{\text{pick}}$ at the origin location $o_{r'}$, a drop-off time $t_{r'}^{\text{drop}}$ at the destination location $d_{r'}$, container volume $q_{r'}$, and delay penalty $c_{r'}^{\text{delay}}$. Transport request r' has the same attributes as the original shipment request r if it is planned to be transported from origin terminal o_r to destination terminal d_r by a flexible service, otherwise, it has different attributes which are decided by the other selected services that are used in combination to transport the shipments.

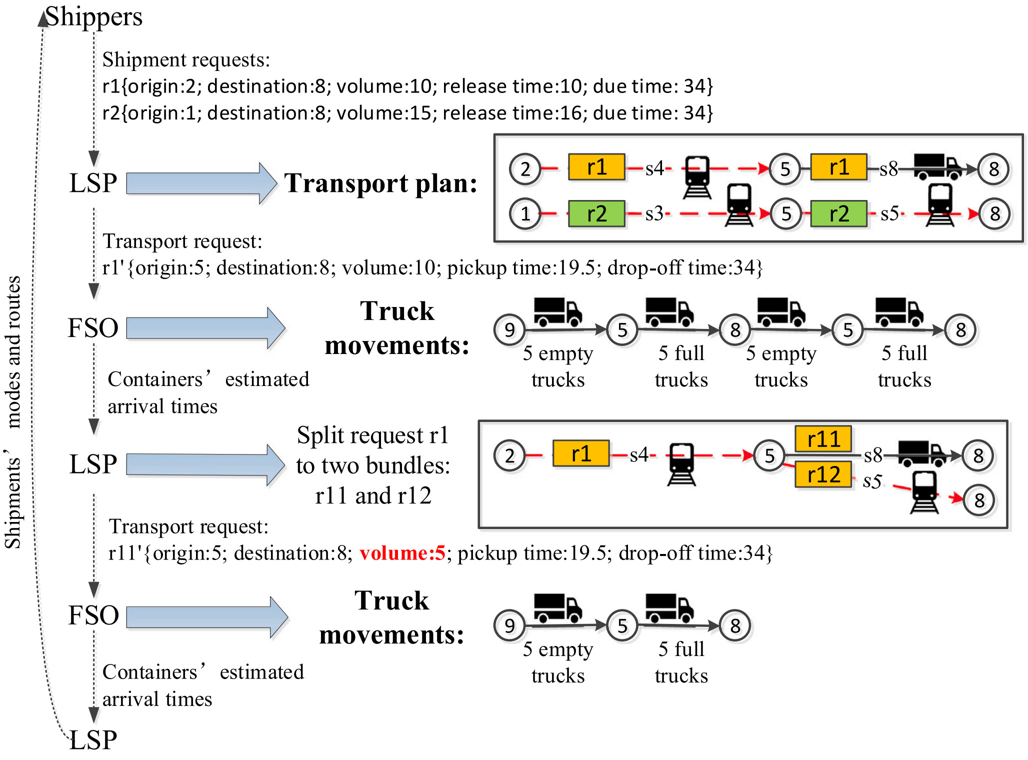

Fig. 2. An illustrative example of a shipment request splitting into two request bundles.

Fig. 2 provides an illustrative example of how LSP and FSO communicate for serving shipment requests with the possibility of splitting them into bundles. First, shippers send two shipment requests r1 and r2 to the LSP. The LSP creates a transport plan in which request r1 will be transported by train service s4 from its origin terminal 2 to transshipment terminal 5, and then transported by truck service s8 from terminal 5 to its destination terminal 8. The LSP thus sends a transport request r1′ from terminal 5 to 8 to the FSO. The FSO creates a truck movement plan to fulfill the transport request. Specifically, the plan indicates that 5 empty trucks move from their current stopping location 9 to the containers' origin location 5, and then carry five containers from location 5 to 8, and then back to location 5 to carry the rest containers of request r1′. The FSO sends back containers' estimated arrival times of request r1′ to the LSP. The LSP thus splits shipment request r1 into two request bundles r11 and r12. Each bundle has 5 containers. While r11 follows the original transport plan by truck s8, r12 will be transported by train service s5. Then, the LSP sends a new transport request r11′ with 5 containers to the FSO. The FSO sends back containers' estimated arrival times. Finally, the LSP sends shipments' mode and route choices to shippers.

The objective of the decentralized container transport system is to minimize the total operational costs for container transportation which consists of the transport costs of scheduled services, the driving costs of flexible vehicles, and the delay costs paid to shippers. A bounded system consisting of a known set of scheduled services, one LSP and one FSO is considered without the possibility of rejecting demand. Moreover, it is assumed that shipment requests arrive in the system continuously in real-time, and transport requests from the LSP to the FSO cannot be rejected and external parties cannot carry out any of the transports. Furthermore, it is assumed that the potential profit of obtaining a system-wide cost reduction is distributed between the parties according to a fair pre-established contract.

4. Decision frameworks: from intermodal planning to synchromodal co-planning

In this paper, we design four different methods to control the decision processes: intermodal, passive synchromodal, active synchromodal, and synchromodal with co-planning. The main difference between intermodal and synchromodal paradigms is the ability to change shipments' mode and route choices. Since the LSP gets new shipment requests of varying priority at different times (often referred to as dynamic demand), changing previous plans can ensure a better overall transport performance. Re-evaluating plans and creating new ones for new requests can happen when they become relevant or at regular intervals. We assume that under all paradigms, the LSP and the FSO evaluate what decisions to reconsider and create new plans periodically. Each such moment where plans are (re)created is denounced a *decision epoch* and the periods between them are denounced a *replanning interval*. The decisions that are re-evaluated at decision epochs and the information that is available to do so differ between different transport paradigms. In all paradigms, the FSO and the LSP take independent decisions based on the information that is available to each of

Table 1
Comparisons of transport paradigms in replanning of decisions and communicated information.

Paradigms	Decisions			Communication	
	LSP		FSO	LSP→FSO	LSP←FSO
	Container mode and route choice	Container departure times	Vehicle routes	Transport requests	Container locations
Intermodal	Fixed	Adjust if arrive late	Reconsider periodically	Once per container	Upon late arrival
Passive synchromodal	Adjust if arrive late	Adjust if arrive late	Reconsider periodically	As necessary	Upon late arrival
Active synchromodal	Reconsider periodically	Reconsider periodically	Reconsider periodically	Periodically	Upon departure & arrival
Co-planning	Reconsider periodically	Reconsider periodically	Reconsider periodically	Periodically	Periodically

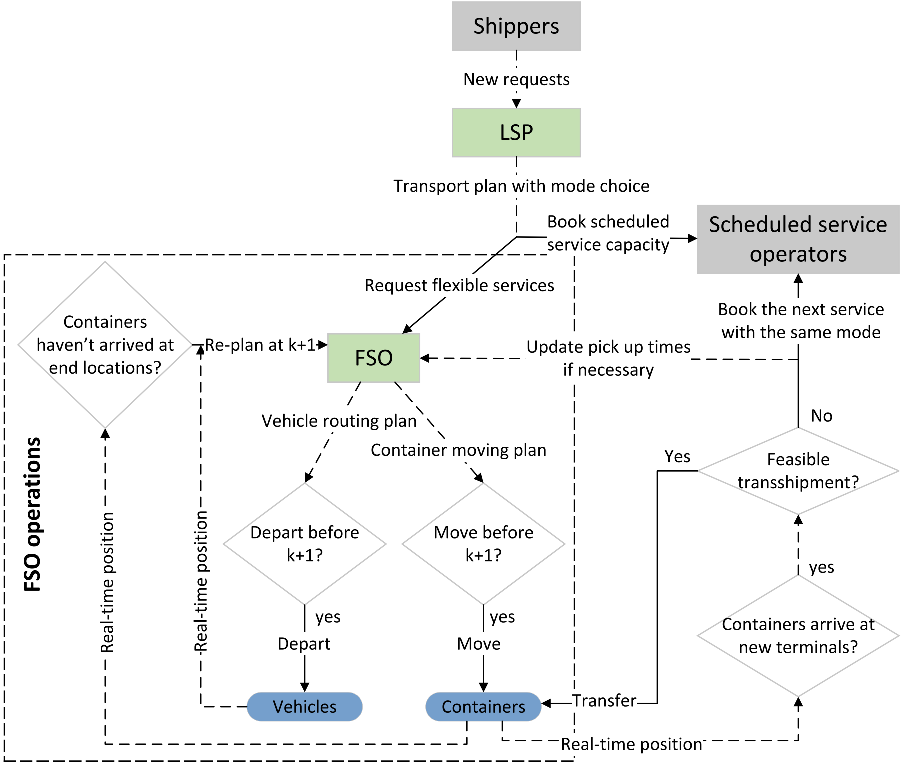

Fig. 3. Schematics of communication (dashed lines) between and actions (solid lines) of the LSP and the FSO in a traditional intermodal transport system.

them at the decision epoch. Table 1 gives an overview of intermodal, active synchromodal, passive synchromodal, and synchromodal with co-planning. In the following, the joint planning problem of an LSP and an FSO is described under each paradigm.

4.1. *Intermodal paradigm*

The cooperation between the LSP and the FSO under a traditional intermodal paradigm is described in Fig. 3. At each decision epoch, the LSP collects all new shipment requests and creates transport plans for them based on the free capacity of scheduled services. The operators of the services used in the plan are then notified of the containers to be transported by them and fulfill the wishes as possible. If the plan for a container becomes infeasible (e.g., there is no available truck or the container arrives after the departure of the scheduled service it was planned for), the operator lets that container wait for the next available service of the mode specified by the LSP. As the FSO's vehicles can depart at any time, the FSO reevaluates their internal plans for all vehicles and containers at every decision epoch even under the intermodal transport paradigm.

4.2. *Synchromodal paradigms*

Under synchromodal transport, plans can be either re-evaluated when it becomes clear that they cannot be executed as intended (*passive synchromodal*) or re-optimized at every decision epoch (*active synchromodal*). Both concepts are represented in Fig. 4. The FSO's internal operations remain the same. In a passive synchromodal transport system, the LSP is notified when a container arrives at a transshipment terminal too late to continue its journey on the intended scheduled service. The LSP will then cancel all future

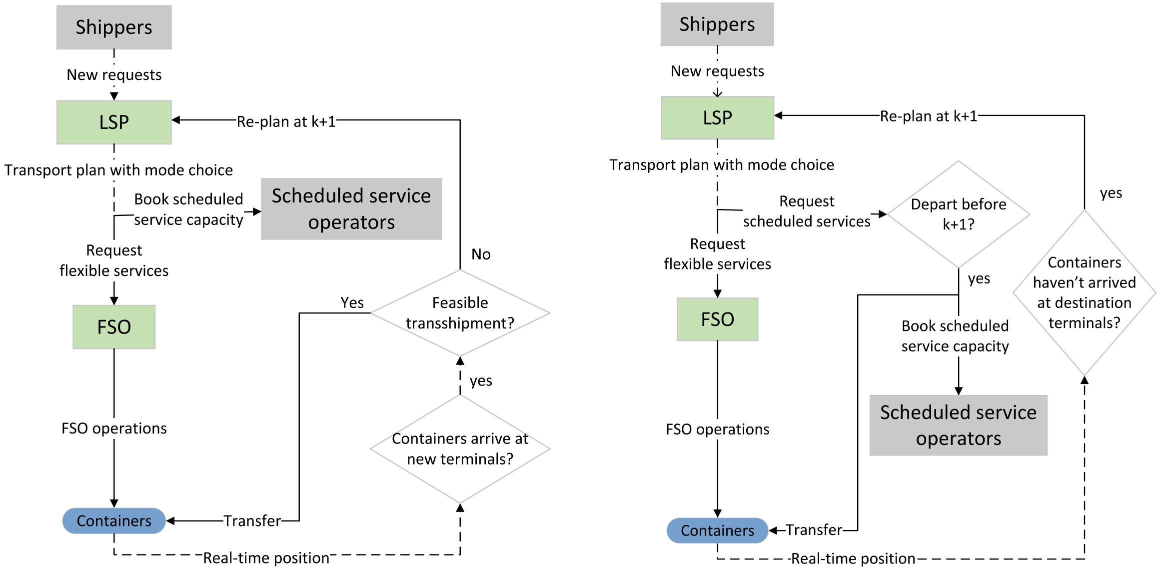

Fig. 4. Schematics of communication between and actions of the LSP and the FSO in passive (left) and active (right) synchromodal transport systems.

bookings for this container and include it in the planning made at the next decision epoch. The transport operators used in the new plan will be notified about the new needed services. In active synchromodal transport systems, the LSP is not only replanned if the initial plan becomes infeasible. Every time a container is at a transshipment terminal, its further route is reconsidered based on the available information on other shipment requests. Notice more information is available at this point in time than when the LSP initially received the container's shipment request. The LSP informs under active synchromodality the transport service operators about upcoming demand at every decision epoch, but only commits to transports that will prepare to depart before the next decision epoch.

4.3. *Synchromodal co-planing paradigm*

When co-planning is added to active synchromodality, the LSP additionally gets feedback on the plans of the FSO. To co-plan, both stakeholders must work towards a common goal by communicating in a realistic manner and without compromising each other's authority. In this case, the common goal is transporting all the containers at the lowest total operation cost and the responsibilities are clearly divided as outlined at the beginning of the section. The communication is kept as it is in current practice, i.e., the LSP only communicates transport requests that they want the FSO to carry out and the FSO only responds to these requests. The communication and authority assumptions prevent global optimization, so the achieved operation cost may not be the lowest possible. Further cost savings are expected if the FSO could suggest container transports where vehicles drive empty, but as it is not current practice, this option is excluded from this research. The communications and actions of the proposed co-planning framework are shown in Fig. 5. The FSO's internal operation and the actions and communication related to the operator of scheduled services do not differ from active synchromodality. At each decision epoch, the LSP requests transports from the FSO who will provide feedback on if the containers can reach their drop-off location in the time the LSP expects. If the containers will be late, the FSO will also inform the LSP on when all containers in the requests are expected to arrive and how many containers will be picked up before the next decision epoch and the expected arrival time of this portion. If there are multiple rounds of communication, the LSP uses this information to replan all shipment requests and the process repeats. The earliest expected arrival time of the containers that will be late is used to compute a lower bound for when that portion of the shipment request can be picked up by the corresponding service. After the last communication round, the feedback from the FSO does not influence the actions taken at the current decision epoch, but it will at the next decision epoch.

5. Co-planning between LSP and FSO

The proposed co-planning framework, outlined in Fig. 5, is detailed in this section. First, the rolling horizon aspect of the method is presented in Section 5.1. In Section 5.2, the communication scheme is presented. The LSP's and the FSO's optimization models are detailed in Sections 5.3 and 5.4, respectively.

A graph representation is used for the transport network where each node is a location, i.e., terminals and hubs. Direct transport connections between two nodes are represented by an arc. If a container is transported from location i passing multiple other locations before ending in j without any possibility of being unloaded, we consider the transport as direct, thus represented by an

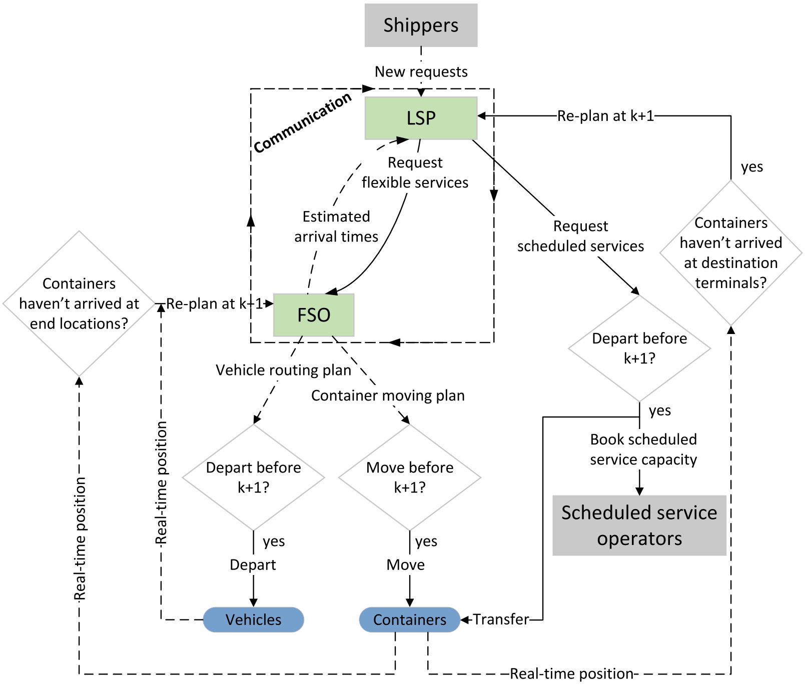

Fig. 5. Communications and actions between the LSP and the FSO under the synchromodal co-planning paradigm.

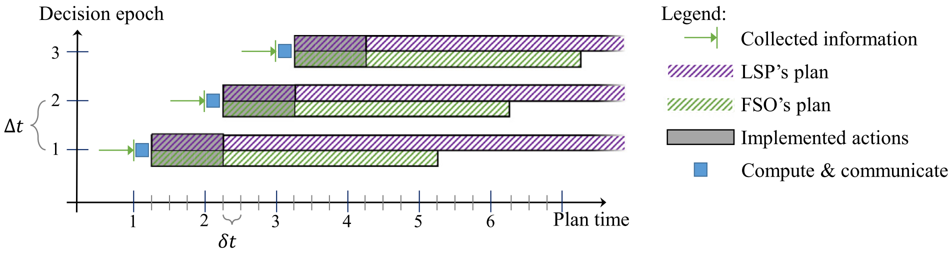

Fig. 6. Illustration of the rolling horizon.

arc. If the container could be unloaded in one of the intermediate locations, the transport consists of one arc for each node where the container could be unloaded. In the mathematical description of the framework, we favor the graph terminology but do occasionally draw parallels to the transport network.

5.1. Rolling horizon method

To facilitate periodic replanning, co-planning uses a rolling horizon. At every Δt hours, the LSP and the FSO plan the movements of containers and vehicles. These decision epochs are indexed with k. The LSP's plan spans over an infinite time horizon, while the FSO plans for the next $T_p\delta t$ hours using a state-space model discretized in time by δt. Here, T_p represents the planning horizon of the FSO. At each decision epoch, the LSP uses the mixed-integer linear programming model presented in Section 5.3 to optimize the transport plan of shipment requests. The FSO uses the state-space model presented in Section 5.4 to optimize the flows of containers and vehicles. This enables the FSO to split transport requests and route each vehicle individually while ensuring continuity and sufficient computation speed. From the plans created by both the LSP and the FSO, only the decisions that are realized before a new plan is available are implemented and all other decisions are reconsidered, as illustrated by Fig. 6. Decisions that are implemented before a given decision epoch cannot be changed, but their consequences are known in the form of future arrivals of containers and vehicles at the end of the arcs they are currently traveling. Shipment requests that are announced before the decision epoch can be incorporated in the plan, while requests that are announced later remain unknown. It is assumed that computing the plans and, in the case of co-planning, communication between the LSP and the FSO takes less than δt hours. At decision epoch k, the earliest a container can be transported is therefore $k\Delta t + \delta t$ hours after the beginning of the simulation.

Algorithm 1 Real-time Synchromodal framework with co-planning

```
for decision epoch $k \in \{1, 2, ..., N^{\text{simulation}}\}$
    LSP receives new shipment requests
    LSP updates active requests $R[k] = R[k-1] \cup R^{\text{new}}[k] \setminus \{r | o_r = d_r\}$
    LSP updates schedules $S^{\text{scheduled}} = S^{\text{scheduled}} \setminus \{s | TD_s < k\Delta t + \delta t\}$
    for each communication round
        LSP optimizes container routes based on LSP's optimization model
        LSP communicates corresponding transport requests, $\hat{\mathcal{R}}^{\text{new}}$, to FSO
            where $\forall r \in \hat{\mathcal{R}}^{\text{new}}$, $\hat{q}_r = q_r$, $\hat{o}_r = \{i | s \in S^{\text{flexible}}_{i+}, \hat{t}_r^{\text{pick-up}} = t_{rs}^{depart}, x_{rs} = 1\}$,
            $\hat{d}_r = \{j | s \in S^{\text{flexible}}_{j-}, \hat{t}_r^{\text{drop-off}} = t_{rs}^{depart} + t_s, x_{rs} = 1\}$
        FSO updates transport request information
        FSO optimizes container and vehicle routes based on FSO's optimization model
        FSO communicates feedback to the LSP
        for all $r \in \hat{\mathcal{R}}^{\text{new}}$
            LSP splits the request if it is transported in different bundles by FSO
            FSO updates volume and drop-off time of the request
        end for
    end for
    for all $\kappa = 1, ..., \frac{1}{\delta t}$ the FSO implements the decisions $\forall r \in \mathcal{R}$:
        $\tilde{\xi}_{rij}(k\Delta t + \kappa\delta t) = \xi_{rij}(\kappa)$, $\tilde{v}_{ij}(k\Delta t + \kappa\delta t) = v_{ij}(\kappa)$,   $\forall i \in H, j \in H_i$,
            (the full updates can be seen in (1)–(3))
    end for
    FSO informs LSP on arrivals of containers
    LSP assumes late containers arrive at time $k\Delta t + \delta t$ and splits the requests
    for departing requests, $r \in \{r \in R \mid \exists s \mid x_{rs} = 1$ and $TD_s \leq (k+1)\Delta t\}$
        $S_r = \{s | x_{rs} = 1$ and $TD_s \leq (k+1)\Delta t\}\}$
        LSP updates information on expected drop off for each $r$, $s \in S$ pair
    end for
end for
```

5.2. Communication scheme

The backbone of the proposed co-planning framework is the ability of the FSO to give feedback to the LSP and the LSP's possibility for adjusting to the feedback. The LSP's and the FSO's individual planning methods are presented in the subsequent sections. The communication between the LSP and the FSO gives the LSP new possibilities to foresee when containers are dropped off before committing to their transport by the FSO. Based on the feedback from the FSO, the LSP can split shipment requests into smaller bundles that fit better with the available transport service capacity (see Fig. 2). Small bundles typically provide cheaper overall transport but increase the computation time of the LSP's planning problem significantly. When using the feedback from the FSO, the LSP can create a few bundles that fit well with the FSO's available transport capacity instead of splitting shipment requests into bundles based on containers' current locations. For each transport request, the containers that the FSO expects to drop off in time, constitute one bundle that will keep the request's properties. The containers that are expected to arrive late will be a similar bundle, but with an earliest pick-up time limit taking into account the earliest availability of trucks. This time limit LB_{rs} regards only the transport of containers from the new request bundle r with the flexible service $s \in S^{flexible}$.

To provide an example, a shipment request r in the LSP's plan made at decision epoch k is scheduled to take a scheduled service from its origin o_r to node i and thereafter a flexible service s from node i to its destination d_r with a pick-up time, $\hat{t}_r^{pick-up}$, and drop-off time, $\hat{t}_r^{drop-off}$. The FSO receives the transport request from node i to d_r and plans vehicle and container movements. The LSP is notified that the plan shows all containers will arrive late at time t_r^{late}. The LSP subtracts the travel time they expect for the service (t_s, transport from node i to d_r) and attaches the departure time lower bound $LB_{rs} = t_r^{late} - t_s$ to the combination of request bundle r and service s. In the next iteration of the communication round, the LSP's plan may still assign request r to service s, just with a later pick-up and drop-off time, or it may assign another mode and route through the network if it is more efficient to do so.

After the communication rounds are over, the FSO implements the actions and adjusts the volumes in the new requests to the number of containers that depart before the next plan is made. The drop-off time is also updated to the expected arrival time that is communicated to the LSP. The optimization and communication process of the proposed co-planning method are outlined in Algorithm 1. Here, we use $N^{\text{simulation}}$ to represent the length of a simulation.

When the FSO's decisions are implemented, the number of containers stacked at any location updates as follows:

$$\tilde{\chi}_{ri}(k + (\kappa+1)\delta t) = \tilde{\chi}_{ri}(k + \kappa\delta t) - \sum_{j \in H_i} \tilde{\xi}_{rij}(k + \kappa\delta t) + \sum_{j \in H_i} \tilde{\xi}_{rji}(k + (\kappa - \tau_{ji})\delta t) + q_r^{\text{accepted}} + q_r^{\text{late}} \text{ for } i = o_r, \tag{1}$$

$$\tilde{\chi}_{ri}(k + (\kappa+1)\delta t) = \tilde{\chi}_{ri}(k + \kappa\delta t) - \sum_{j \in H_i} \tilde{\xi}_{rij}(k + \kappa\delta t) + \sum_{j \in H_i} \tilde{\xi}_{rji}(k + (\kappa - \tau_{ji})\delta t), \quad \forall i \in H \setminus \{o_r\}. \tag{2}$$

The number of trucks parked at each location is similarly:

$$\tilde{\rho}_i(k+(\kappa+1)\delta t) = \tilde{\rho}_i(k+\kappa\delta t) - \sum_{j\in H_i} \tilde{\upsilon}_{ij}(k+\kappa\delta t) + \sum_{j\in H_i} \tilde{\upsilon}_{ji}(k+(\kappa-\tau_{ji})\delta t), \quad \forall i \in H. \tag{3}$$

5.3. LSP's optimization model

The LSP receives shipment requests for transports of high quantity, spanning long periods of time. Therefore, the LSP uses a matching model to optimize the routes of the containers through the synchromodal transport network. We state the LSP's optimization problem without indicating the time the decision is taken for the ease of notation. This means that at any time k, e.g., R is the set of shipment requests on which the LSP can take decisions at this decision epoch k and the variable $x_{rs} = 1$ if in this plan the containers from request r is transported by service s from the set of all services S. Scheduled services are only available according to their schedules while flexible services are considered always available unless feedback from the FSO has led to the formulation of an earliest pick-up time limit LB_{rs}. The LSP does not split requests as part of the planning problem, but before each decision epoch, the LSP is notified of departures and arrivals of containers. If the containers of a shipment request r are estimated to arrive at different places, e.g., some at a node and some being transported by the FSO, the LSP splits the request into bundles that appear as separate requests r' and r'' in set R. These bundles can be split again later on but never merged.

$$\min \sum_{r\in R}\sum_{s\in S} x_{rs} q_r c_s + \sum_{r\in R} t_r^{\text{delay}} q_r c_r^{\text{delay}} \tag{4}$$

subject to

$$\sum_{s\in S_{o_r}^+} x_{rs} = 1, \quad \forall r \in R, \tag{5}$$

$$\sum_{s\in S_{d_r}^-} x_{rs} = 1, \quad \forall r \in R, \tag{6}$$

$$\sum_{s\in S_i^+} x_{rs} = \sum_{s\in S_i^-} x_{rs}, \quad \forall r \in R, i \in N\backslash\{o_r, d_r\}, \tag{7}$$

$$\sum_{r\in R} x_{rs} q_r \le Q_s, \quad \forall s \in S^{\text{scheduled}}, \tag{8}$$

$$t_{ro_r} = t_r^{\text{release}}, \quad \forall r \in R, \tag{9}$$

$$t_{ri} \le TA_s + M\left(1 - x_{rs}\right), \quad \forall r \in R, i \in N\backslash\{o_r\}, s \in S_{i-}^{\text{scheduled}}, \tag{10}$$

$$t_{ri} \ge TA_s + M\left(x_{rs} - 1\right), \quad \forall r \in R, i \in N\backslash\{o_r\}, s \in S_{i-}^{\text{scheduled}}, \tag{11}$$

$$t_{ri} \le t_{rs}^{depart} + t_s + M\left(1 - x_{rs}\right), \quad \forall r \in R, i \in N\backslash\{o_r\}, s \in S_{i-}^{\text{flexible}}, \tag{12}$$

$$t_{ri} \ge t_{rs}^{depart} + t_s + 2M\left(x_{rs} - 1\right), \quad \forall r \in R, i \in N\backslash\{o_r\}, s \in S_{i-}^{\text{flexible}}, \tag{13}$$

$$t_{ri} \le TD_s + M\left(1 - x_{rs}\right), \quad \forall r \in R, i \in N\backslash\{d_r\}, s \in S_{i+}^{\text{scheduled}}, \tag{14}$$

$$t_{ri} \le t_{rs}^{depart} + M\left(1 - x_{rs}\right), \quad \forall r \in R, i \in N\backslash\{d_r\}, s \in S_{i+}^{\text{flexible}}, \tag{15}$$

$$t_r^{\text{delay}} \ge t_{rd_r} - t_r^{\text{due}}, \quad \forall r \in R, \tag{16}$$

$$t_{rs}^{depart} \ge LB_{rs} + M\left(x_{rs} - 1\right), \quad \forall r \in R, s \in S^{\text{flexible}}. \tag{17}$$

The LSP optimizes the transport cost and the fees for late delivery in the objective function (4). Here, q_r is the volume of containers in request r, c_s is the cost of transporting one container with service s, c_r^{delay} is the fee per hour for delivering one container from request r late, and t_r^{delay} is the lateness of request r. Constraints (5)–(7) ensure all containers are transported from their origin to destination. From each node i in the set of terminals N, a set of services depart S_i^+ and arrive S_i^-. o_r is the origin of shipment request r until the request is released. After release, o_r is either the location of request r if it is at a node, or the destination of the scheduled service if r is being transported by a scheduled service, or the drop-off location of the transport request if the FSO is transporting request r. d_r is the destination of shipment request r. The LSP restricts with constraints (8) how many containers are planned for a scheduled service based on their exact knowledge of the service capacity Q_s.

Shipment request r's release time t_r^{release} reflects the earliest time it can be picked up at its current o_r. If the request is staying at a node, it is the current time; if the request is being transported by a scheduled service, it is the arrival time of that service; if request r is being transported by the FSO, t_r^{release} is the expected drop-off time of the transport request. In case the containers do not arrive in time, the LSP misses the arrival notification and will thereafter expect the containers to arrive δt hours after the decision epoch. The connection between the first place and time of request r in the plan is ensured by constraints (9). The arrival time t_{ri} of request r at location i is ensured to match the arrival time TA_s of the scheduled service that transports it by constraints (10)–(11), while constraints (12)–(13) match it with arrival times of the relevant flexible services. The variable t_{rs}^{depart} is the departure time of request r with the flexible service $s \in S^{\text{flexible}}$. Constraints (14)–(15) ensure that the departure time of request r at terminal i must be later than its arrival time. Constraints (16) count how long after its due time t_r^{due}, the containers from shipment request r arrives. Constraints (17) ensure that the departure time of request r with the flexible service $s \in S^{\text{flexible}}$ must be later than the earliest pickup time limit LB_{rs}.

5.4. FSO's optimization model

The FSO not only has to route the containers through their network but also the full and empty vehicles. To do so efficiently, the FSO uses a state-space model that describes the dynamics of the system over a prediction horizon T_p that is discretized into what we denote *planning-time steps* each spanning δt hours, i.e., at every decision epoch, the FSO plans for the next $T_p\delta t$ hours and implements actions corresponding to the next $\frac{\Delta t}{\delta t}$ planning-time steps. The value of δt is generally smaller than the value of Δt to allow for a fine discretization of time in the LSP optimization model without needing to compute new plans and communicate as frequently. We use κ to indicate the planning-time steps in the FSO's plan. We state the FSO's optimization problem without indicating in the notation the time the plan is made to ease the notation. For a plan made at decision epoch k, $\xi_{rij}(\kappa)$ is thus the number of containers from transport request r that are planned to be loaded on a vehicle that departs $k\Delta t + \kappa\delta t$ hours after the simulation starts from node i to j. We assume (un)loading time to be included in the transport time. When necessary, the decision epoch is indicated with $[k]$ after the general notation. The set of transport requests from the LSP to the FSO that are currently being transported or that are new requests at decision epoch k is thus denoted by $\mathcal{R}$ when the decision epoch is clear and $\mathcal{R}[k]$ otherwise. The parameters and variables that are exclusive to the FSO's optimization problem are denoted with Greek letters to increase clarity. Indices are marked with superscripts differentiating similar variables/parameters, e.g., different kinds of costs. Only flexible services with the same travel time and capacity can operate on an arc. Vehicles with different characteristics transporting between the same nodes can be modeled by duplicating the nodes.

$$\min \sum_{i\in H}\left(\sum_{\kappa=1}^{T_p-1}\left(\sum_{j\in H_i}(1+\omega^e\frac{\kappa}{T_p-1})\omega^{v}_{ij}\upsilon_{ij}(\kappa) + \sum_{r\in\mathcal{R}\setminus\{r|d_r=i\}}\omega^s\chi_{ri}(\kappa+1) + \sum_{r\in\mathcal{R}}\left(\hat{c}_r+\omega^d\right)\psi_{ri}(\kappa+1)\right)\right.$$
$$\left.+\sum_{r\in\mathcal{R}}(1+\omega^e)\omega^{direct}_{id_r}\left(\chi_{ri}(T_p)+\sum_{j\in H_i}\sum_{l\in[1,\dots,\tau_{id_r}]}\xi_{rji}(T_p-l)\right)\right) \tag{18}$$

subject to

$$\chi_{ri}(1) = \tilde{\chi}_{ri}(k),\ \rho_i(1) = \tilde{\rho}_i(k),\ \xi_{rij}(-l) = \tilde{\xi}_{rij}(k-l\delta t),\ \upsilon_{ij}(-l) = \tilde{\upsilon}_{ij}(k-l\delta t),$$
$$\forall\, l\in[0,\dots,\tau_{ij}],\ \forall\, i\in H,\ \forall\, j\in H_i, \forall\, r\in\mathcal{R}[k]\cup\mathcal{R}[k-1], \tag{19}$$
$$\chi_{ri}(1) = \phi^+_{ri}(1),\ \xi_{rij}(-l) = 0,$$
$$\forall\, l\in[0,\dots,\tau_{ij}],\ \forall\, i\in H,\ \forall\, j\in H_i,\ \forall\, r\in\mathcal{R}[k]\cap\mathcal{R}[k-1], \tag{20}$$
$$\psi_{ri}(1) = \phi^-_{ri}(1),\ \forall\, i\in H,\ \forall\, r\in\mathcal{R}[k], \tag{21}$$
$$\forall\, i\in H,\ \forall\,\kappa\in[1,\dots,T_p-1]:$$
$$\chi_{ri}(\kappa+1) = \chi_{ri}(\kappa) - \sum_{j\in H_i}\xi_{rij}(\kappa) + \sum_{j\in H_i}\xi_{rji}(\kappa-\tau_{ji}) + \phi^+_{ri}(\kappa+1) - \epsilon_{ri}(\kappa),\ \forall\, r\in\mathcal{R}, \tag{22}$$
$$\rho_i(\kappa+1) = \rho_i(\kappa) - \sum_{j\in H_i}\upsilon_{ij}(\kappa) + \sum_{j\in H_i}\upsilon_{ji}(\kappa-\tau_{ji}), \tag{23}$$
$$\psi_{ri}(\kappa+1) = \psi_{ri}(\kappa) - \epsilon_{ri}(\kappa) + \phi^-_{ri}(\kappa+1),\ \forall\, r\in\mathcal{R}, \tag{24}$$
$$\sum_{r\in\mathcal{R}}\xi_{rij}(\kappa) \le \gamma_\upsilon\upsilon_{ij}(\kappa),\ \forall\, j\in H_i. \tag{25}$$

The FSO optimizes, as given in (18), the predicted cost of operating their vehicles and late delivery. The FSO furthermore promotes early transport of containers by adding a fee for transporting later. This is added as a small percentage increase, ω^e, to the travel cost ω^{v}_{ij} for all $i\in H$ and $j\in H_i$. Here, H denotes hubs and terminals in the flexible mode's network, $N\subseteq H$; H_i denotes the set of nodes reachable from node i by flexible service; ω^{v}_{ij} denotes the cost of operating a vehicle, regardless of its load, from node $i\in H$ to a node j in the set of nodes connected to i by the FSO's transport network H_i. At each location except the destination of the request, a stacking and (un)loading cost, ω^s, is applied to each container each time step. This cost is an average estimate based on historical data. Furthermore, the stacking cost promotes early departures. d_r is the destination and $\hat{c}_r$ is the fee for late arrival of request $r\in\mathcal{R}$ received from the LSP. In addition to the fee for late arrival, an internal cost of not satisfying demand, ω^d, drives the system.

The last term in the objective function estimates the cost the containers will cause after the end of the plan, this makes plans with shorter planning horizons, T_p, more accurate. It is a well-known technique from model predictive control that has been adapted to transport contexts, e.g., in Li et al. (2015). A long planning horizon increases significantly the computational complexity of the optimization problem. The used estimate is optimistic in the sense that it penalizes the containers that are not at their destination at the end of the plan with the minimum remaining travel cost ω^{direct}_{ij} from node i to j. If no direct arc exists, it is the cost of the shortest path between the nodes. It does as such not reflect the true operation cost as that includes repositioning empty trucks, but it is computationally tractable.

$\upsilon_{ij}(\kappa)$ is the number of vehicles leaving node i at time step κ in the plan towards node j. $\chi_{ri}(\kappa)$ is the number of containers from transport request r that is planned to be stacked at node $i\in H$ at time $k\Delta t+\kappa\delta t$. Loading fees are assumed to be paid by the LSP as part of the service cost. The number of containers from request r that should have been dropped off at node i before time $k\Delta t+\kappa\delta t$ but has not yet arrived is denoted by $\psi_{ri}(\kappa)$. τ_{ij} is the travel-time from node $i \in H$ to node $j \in H_i$ including potential (un)loading.

The FSO plans according to the current state of the transport system. Therefore we need to distinguish between planned values and realized values. The latter we denote with a tilde, such that, e.g., $\tilde{\chi}_{ri}(k)$ is the number of containers from trucking request r that is stacked at node i at time $k\Delta t$. The planned number of trucks parked at node i at planning-time step κ is $\rho_i(\kappa)$, while the realized number parked at decision epoch k is $\tilde{\rho}_i(k)$. $\tilde{\psi}_{ri}(k)$ is the number of containers from request r that are still missing to be delivered after their drop-off time at node i at decision epoch k. The initial state of the transport system is in (19) set to be the current state of the containers the FSO has previously committed to transport but not dropped off and of the vehicles, and in (20) to the new transport requests. (21) initiates the demand for both new and already picked-up requests. The dynamics of the number of containers, vehicles, and unsatisfied demand in each node are described by (22)–(24). $\epsilon_{ri}(\kappa)$ is the number of containers from request r that arrive at their drop off location, $d_r = i$, at time $k\Delta t + \kappa\delta t$. The number of containers from transport request r that requested to be picked up at node i at time $k\Delta t+\kappa\delta t$ is denoted by $\phi^{+}_{ri}(\kappa)$ and the corresponding requested drop-offs are $\phi^{-}_{ri}(\kappa)$. (25) states that containers can only travel over an arc if there are sufficient vehicles to transport them. γ_v is the capacity of the vehicles that operate the arc from node i to j.

6. Case study and numerical experiments

To demonstrate the impact of co-planning between an LSP and an FSO, a set of numerical experiments is designed based on a case study. For this purpose, benchmarks are developed representing the intermodal, passive synchromodal, and active synchromodal methods introduced in Section 4. In all four methods, the FSO reconsiders all decisions at every decision epoch by solving (18)–(25) and informs the LSP about the expected arrival times upon departures of containers. Under intermodal, passive synchromodal, and active synchromodal, the LSP optimizes (4)–(16) to update the routing of containers and splits shipment requests into bundles based on the containers' current locations when their routes are to be reconsidered. Under these paradigms, the goal of the LSP is to minimize the cost of late delivery of containers and the cost of using transport services, while the FSO minimizes the cost of moving empty and full vehicles, transshipment and stacking of containers as well as late arrivals of containers according the LSP's shipment requests. There is no central coordination and each stakeholder takes decisions based on the information that is locally available.

The faster the LSP and the FSO can optimize the routing problems, the more frequent the decision epochs can be kept and the more rounds of communication are possible for each decision epoch. The heuristic presented by Guo et al. (2020) is used to decrease the computational complexity of the LSP's routing problem. It preprocesses the data to establish a set of feasible combinations of services for each request. The maximum number of services one request can use is furthermore limited to three, as sensitivity analysis on this parameter in Guo et al. (2020) shows three is a good trade-off between optimality and computational time for a similar geographical network.

The approaches are implemented in MATLAB, and all experiments are executed on 3.70 GHz Intel Xeon processors with 32 GB of RAM. The LSP uses CPLEX 12.6.3 to solve its optimization problem. The FSO uses Yalmip with Gurobi 9.5.2 to solve the FSO's optimization problem. Two different solvers are used to emphasize the disconnect between the two different optimization problems. The planning problems of the LSP and the FSO belong to two different organizations, that may have very different internal methods and tools.

In this section, first the experimental setup is presented. The impact of different transport paradigms on transport planning under a case study are presented next which is then followed by the results of the numerical experiments on larger instances. For this purpose, sensitivity analysis is performed first under different method-parameter settings and second under different scenario parameters such as fleet size, lead times, and delay fees. In these analyses, the performance of the proposed approach is compared to the benchmark methods.

6.1. Experimental setup

The geographical network used in the numerical experiments is presented in Fig. 7. The top network displays the locations of interest to the LSP, the scheduled services operating between them, and the origin–destination pairs of shipment requests. To ease the presentation of results, the FSO provides unimodal truck transport where one vehicle can carry one container, i.e., $\gamma_v = 1$. The lower network shows the roads used in the FSO's planning problem with the travel times that result from the time-invariant state-space model planning methods. The road network has additional locations where trucks can park and containers can be stacked.

The travel times, costs, and other network parameters are adopted from Guo et al. (2020) and based on existing practices. The cost and travel time for road transport are seen in Table 2. In the upper triangle of the left matrix are the travel times used in the LSP's planning problem. In the lower triangle are the actual travel times known by the FSO. If no time is indicated, the LSP, respectively the FSO, do not use a direct connection between the indicated nodes in their planning problem. The upper triangle of the right matrix shows the cost the LSP assumes for road transport of a container between the two indicated nodes, while the lower triangle shows the actual cost for transversing the arc with a vehicle. The LSP's estimated travel cost includes (un)loading costs and assumes the FSO's vehicles drive empty 50% of the distance. Transversing an arc takes the same time and costs in both directions. At the beginning of the simulation, i.e., before the first decision epoch, no shipment requests are known and all trucks are parked at one node. In the case study, 10 trucks are parked in node 9, Dortmund, and in the large-scale experiments, 25 trucks are parked in node 1, Maasvlakte I.

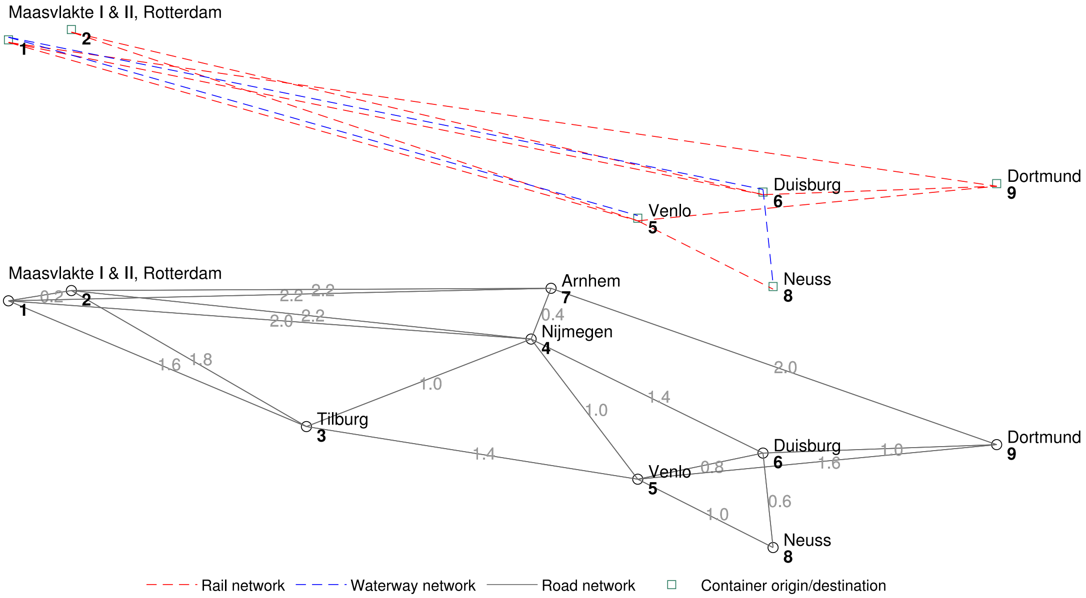

Fig. 7. Transport network used in all experiments. The road network is only known by the FSO.

Table 2
Travel times and costs for truck transport between nodes.

	1	2	3	4	5	6	7	8	9
1	0	0.2			2.6	3.2		3.5	4
2	0.2	0			2.8	3.3		3.6	4.2
3	1.57	1.71	0						
4	1.95	2.08	0.93	0					
5			1.24	0.87	0	0.8		0.9	1.5
6				1.28	0.8	0		0.5	0.9
7	2.07	2.19		0.33			0		
8					0.9	0.5		0	
9					1.5	0.9	1.95		0

LSP travel time [hours]

FSO direct travel time [hours]

	1	2	3	4	5	6	7	8	9
1	0	17			140	171		187	213
2	52	0			151	176		192	223
3	41	44	0						
4	50	54	24	0					
5			32	22	0	47		53	84
6				33	21	0		32	53
7	53	56		9			0		
8					23	13		0	
9					39	23	50		0

LSP travel cost [€]

FSO direct travel cost [€]

We also list a baseline experimental setup that is used unless otherwise stated. Each experiment is repeated 10 times, each with a different set of requests drawn from the same distribution. In all experiments, the decision epochs occur every hour, i.e., $\Delta t = 1$, for all methods and with two rounds of communication for co-planning. With two rounds of communication, the LSP adjusts its plan according to the feedback from the FSO once before the immediate actions are implemented. The dynamics of FSO's transport system are in the experiments discretized using $\delta t = 0.2$ h and the FSO's optimization problem considers $T_p = 50$ planning time steps. The baseline delay cost is $\omega^d = 1000$, the storage cost $\omega^s = 0.2$ and the penalty used to promote earlier actions in the FSO's optimization problem is $\omega^e = 0.001$. The delay cost known to the FSO is the true delay cost of the request $\hat{c}_r = c_r^{delay}$.

6.2. Case study

In this section, a small case study with few transport requests and limited services are presented to provide an overview of the strengths and weaknesses of co-planning and the benchmark paradigms. The benchmark paradigms are implemented as introduced in Section 4 with the LSP's optimization problem being solved via (4)–(16) without (17). The request data and service data are presented in Table 3.

When plans are adapted differently under the four transport paradigms, the resulting actions in the transport system also differ. Fig. 8 shows the realized movements of containers and trucks in the case study. Each of the nine locations in the transport network appears on the horizontal axes of the figure without respecting distances and network structure. The time dimension appears on the vertical axes. The black lines show the position of the FSO's trucks. The width of the black lines indicates how many trucks are at a given location or in transit. For example, under the intermodal paradigm, all the trucks drive from node 9 to 1, while under co-planning, only some drive from node 9 to 5, and the remaining stay parked at node 9. For scheduled barge and train services, the width of the lines indicates how many containers are transported by the service. If a scheduled service is not used, it appears as a dotted line. The two routes of the containers from the two shipment requests are marked with yellow and green respectively.

Table 3
Request data and service data in the small case study.

Requests	Origin	Destination	Volume	Announce time	Release time	Due time	Delay cost		
rowhead r1	2	8	10	8.0	10.0	34.0	5.00		
r2	1	8	15	14.0	16.0	34.0	10.00		
Scheduled services	Mode	Origin	Destination	Capacity	Departure time	Arrival time	Transit time	Transit cost	Distance
s1	Barge	1	5	30	12.0	27.0	15.0	48.11	195.0
s2	Barge	1	5	30	36.0	51.0	15.0	48.11	195.0
s3	Train	1	5	30	16.0	22.0	6.0	77.59	180.0
s4	Train	2	5	30	12.0	18.5	6.5	82.79	202.5
s5	Train	5	8	20	30.0	33.5	3.5	51.60	67.5
s6	Train	5	8	20	54.0	57.5	3.5	51.60	67.5
Flexible services	Mode	Origin	Destination			Estimated transit time		Transit cost	Distance
s7	Truck	2	1				0.2	16.95	15.0
s8	Truck	5	8				0.9	52.50	67.5

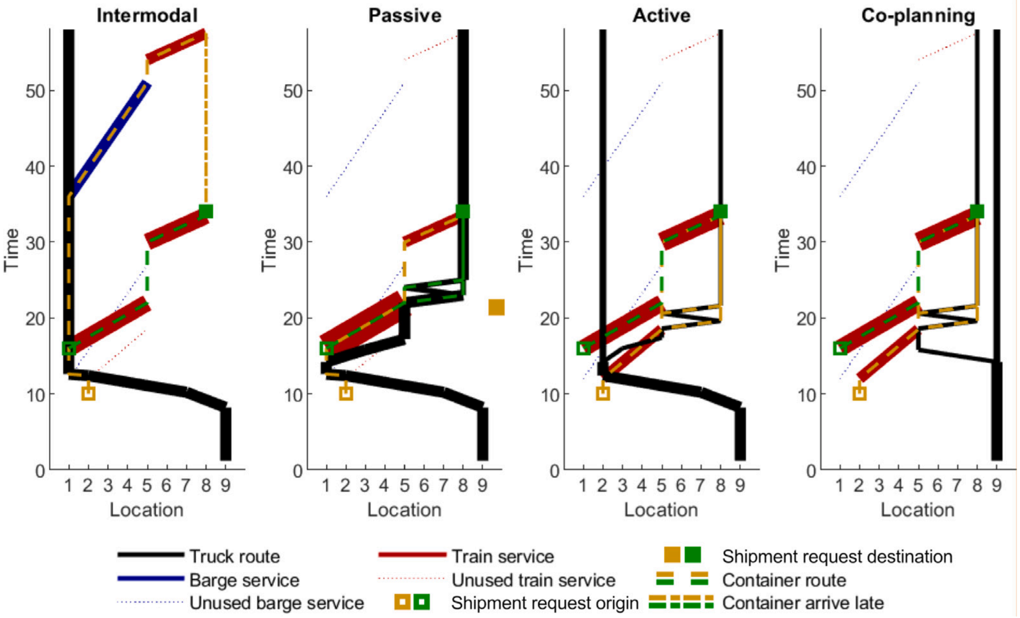

Fig. 8. The routes of containers and vehicles under each of the four transport paradigms.

In the example, the LSP expects that the containers from the yellow shipment (r1) can be picked up by a truck (s7) and transported to node 1 in time to take the barge (s1) which departs from there at time 12. However, as all trucks initially are far away (at node 9) and the shipment is requested at time 8, the containers cannot be picked up before time 12.4, making them unable to reach the barge (s1) in time. Under intermodal transport, the containers stay at node 1 until the next barge (s2) becomes available. This leads to the containers arriving at their destination late (arrival: 57.5, due date: 34) and a very inefficient use of trucks. All trucks drive the long way from node 9 to 2, while a single truck would be able to transfer all containers from node 2 to 1 in the available time before the second barge (s2) departs. The green shipment request (r2) is announced after it becomes clear that the yellow request (r1) will be late and rescheduled to take the later departure of the initially assigned modality (barge). It is therefore known that the train (s5) from node 5 to 8 leaving at time 30 has enough capacity to transport all containers in the green request.

Under passive synchromodal transport, the late arrival of the containers to node 1 causes the LSP to consider the yellow order (r1) as part of the plan made at the next decision epoch. This results in the mode being changed from barge (s1) to train (s3) traveling from node 1 to 5. The cheapest route continues with a train service (s5) from node 5 to 8. This train has limited capacity, so when the green shipment request (r2) is announced, there is not enough capacity left to transport these containers. The green containers (r2) are thus transported by the more expensive truck mode (s8) instead. This increases the total cost of transport as there are more containers in the green shipment request (r2) than in the yellow (r1). Under passive synchromodal transport, all containers arrive at their destinations in time, but again, more trucks are used than what is needed resulting in an unnecessary

Table 4
Additional results for the small case study.

Paradigm	Actual cost	Change	Estimated cost	Truck utilization	Truck distance	Change
Intermodal	5722€		4761€	2.31%	3250 km	
Passive	5401€	−6%	3894€	17.32%	6712 km	107%
Active	4568€	−21%	3289€	11.26%	4795 km	48%
Co-planning	3351€	−42%	3289€	42.86%	1260 km	−61%

low truck utilization (distance driven full over total distance). Compared with the intermodal paradigm, the plan under the passive synchromodal paradigm benefits from mode changes when containers arrive late at transfer nodes.

In contrast to the passive synchromodal paradigm, the LSP's plans are reconsidered periodically under the active synchromodal paradigm. At decision epoch 12, the LSP knows that the containers from the yellow shipment request (r1) are still at node 2, and thus cannot reach the first barge (s1) from node 1. The route of the containers is changed to go by the train (s3) departing immediately from node 2. After the green shipment request (r2) is announced, both requests are part of the planning problem. Since there are more containers in the green shipment request (r2), they are assigned to the train (s3) from node 5 to 8 leaving at time 30 and the yellow (r1) is to be transported by truck (s8). The FSO thus receives a transport request from node 5 to 8 with a sufficiently long time between pick up and delivery. Therefore, the FSO only sends a few trucks from node 2 to 5. The decision epoch after some of the yellow containers have been picked up at node 5, the LSP replans based on the information that some of the containers are still at location 5. This results in a new request to the FSO for transporting the remaining yellow containers. The FSO has (as they predicted earlier) enough time to use the trucks that have dropped off the first batch of yellow containers at node 8 to pick up some of the remaining containers. The distance from node 8 to 5 is smaller than that from node 2 to 5, so this is the most economical decision. After the FSO has picked up the second batch of yellow containers, only a few containers are left in node 5. When the LSP now does the periodic replanning, these remaining containers can fit on the train leaving node 5 at time 30. The periodic reconsideration of the LSP's plan ensures a cheaper transport of the containers as they can use barge and train for more of their journeys. It also improves the truck utilization rate, as fewer containers are to be transported from node 5 to 8, allowing the FSO to let some trucks remain parked at node 2.

When the LSP and the FSO communicate under co-planning, the containers follow the same route as under the active synchromodal paradigm. However, the truck usage is significantly improved. The FSO lets the LSP know that the trucks cannot pick up the containers from the yellow shipment (r1) in time to reach the barge (s1) leaving node 1 at time 12. Since the LSP replans based on this knowledge before committing to any actions, the containers from the yellow shipment are immediately rescheduled to take the train (s3) instead of the barge. The FSO is thus never asked to transport anything from node 2, which prevents the unnecessary relocation of trucks to node 2 as in the case of the active synchromodal paradigm. In this way, the empty truck travel distance is significantly reduced, in turn, the total operation cost of the co-planning paradigm is lower than the active synchromodal paradigm.

The economic impacts of co-planning and the benchmark paradigms can be seen in Table 4. With more flexibility, the total cost of operating the transport system decreases by 21% with active synchromodality compared to the intermodal paradigm. Adding co-planning decreases the cost additionally by 21% on top of the cost of the active synchromodal transport. It is shown with the case study that, communication (using co-planning) is as important for decreasing the operation cost as the planning flexibility (active synchromodal instead of intermodal paradigm). The total costs include the spot prices paid for the transport of containers on scheduled services, driving full and empty trucks, and penalties paid by the LSP for late delivery of containers.

The LSP expects a fixed cost of c_s ($\forall s \in S^{\text{flexible}}$) per container to use a flexible service between the pick-up and drop-off location. The true operation cost of the service is more complex, as the FSO may have to drive empty to the pick-up location. There is therefore a significant gap between the cost the LSP expects and the actual cost. In intermodal transport, the mode choice does not change, and the gap is a moderate 18% while for both active and passive synchromodal transport it is 28%. Co-planning reduces the gap significantly to only 2%.

Co-planning also improves truck utilization significantly, i.e., trucks more often drive full compared to the total distance they drive. The total distance driven is, furthermore, significantly lower than under other paradigms. It is noteworthy that the utilization rate under passive synchromodality is higher than under active, at the same time the distance driven is also higher, so the distance the trucks drive empty is higher under passive than active synchromodal transport. This is because only the shipment requests that cannot make their next planned service are replanned under passive synchromodality, while all shipment requests are replanned at every decision epoch under active synchromodality. So while it looks like the efficiency of the truck fleet is better under passive synchromodal transport, the cost of road transport and its environmental impact is better under the active synchromodal paradigm. Overall, the flexibility and coordination in co-planning outperform the other paradigms in the case study.

6.3. Numerical experiments with larger instances

In the following sections, results for larger instances are presented. The details on the scheduled services used in the large-scale experiments are shown in Table 5. Each route consists of two locations, between which two identical vehicles travel. The vehicles depart at the same time from either location. Barge services are cheaper than train services, but have longer travel times.

Table 5
Scheduled services available to the LSP.

Mode	Routes	Capacity	First departure	Frequency	Travel time [h]	Cost per container [€]
Barge	5-1, 1-5	100	12	24	15.0	48.11
	6-1, 1-6	100	10	24	18.0	50.91
	8-6, 6-8	50	52	48	4.5	38.33
Train	5-1, 1-5	100	16	24	6.0	77.59
	6-1, 1-6	100	38	24	8.0	98.39
	9-1, 1-9	100	34	48	9.0	108.78
	5-2, 2-5	100	12	24	6.5	82.79
	6-2, 2-6	100	10	24	8.5	103.58
	8-5, 5-8	50	52	48	3.5	51.60
	9-5, 5-9	50	52	48	4.5	61.99
	9-6, 6-9	50	60	48	3.5	51.60

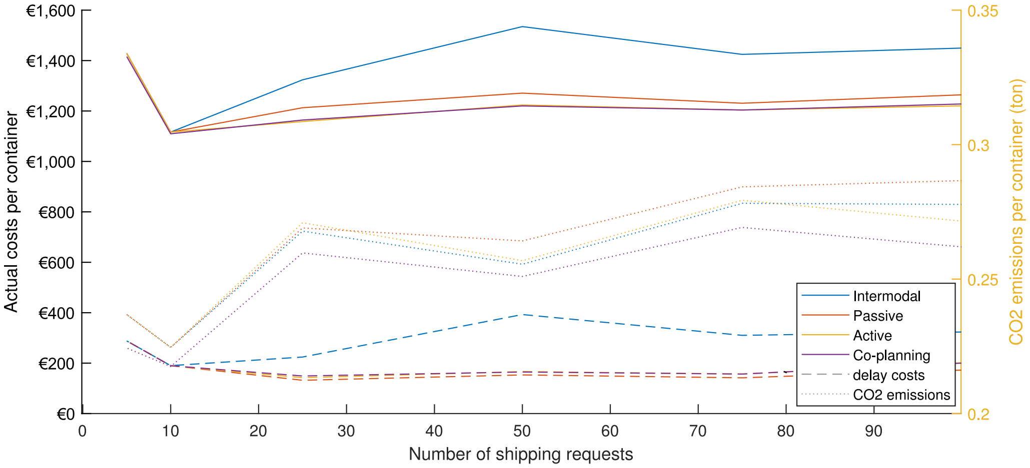

Fig. 9. The average operation cost, delay cost, and CO2 emissions per container under each paradigm in scenarios with different numbers of shipment requests.

For these larger experiments, 10 collections of 25 shipment requests are used, one for each repetition of the experiments. 25 requests were used, as initial experiments using 20 trucks and one repetition indicate that this is the lowest number of requests for which the operational cost and delay cost per container are stable under passive synchromodality, active synchromodality, and co-planning, as seen in Fig. 9. All requests are released immediately after they are announced. The attributes of each request are randomly drawn. The probability of a request originating in Rotterdam is 75% with an equal split between node 1 and 2. These requests have an even probability of being due at node 5, 6, 8, and 9. Reversely, there is a 25% probability the request origins in either node 5, 6, 8, or 9 with an even chance between them and has a destination in node 1 or 2, also with an even chance between them. The number of containers in the request q_r is drawn from a uniform distribution between 1 and 19. The difference between the announce time of a request and the following request is drawn from a Poisson distribution with a mean of 45 min. The release time, $t_r^{release}$, is the decision epoch following the announce time and the due time t_r^{due} is 12 to 14, 18 to 20, or 24 to 26 h thereafter with an even probability between the intervals and a normal distribution within the intervals. Requests with a lead time of 13 h have delay cost $c_r^{delay} = 15$, 19 h have $c_r^{delay} = 10$, and 25 h have $c_r^{delay} = 5$ following the assumption that short lead times imply urgency and priority. The total volume of containers to be transported is between 220 and 299 in the request sets.

6.3.1. *Sensitivity to method parameters*

For both co-planning and the benchmark methods, the time interval between replanning (Δt) is a core parameter. How many times the plans are communicated (N^{com}) between the LSP and the FSO at each decision epoch before a decision is implemented is an additional core parameter for co-planning. In this section, the sensitivity to both of these parameters is described. Parameters that are specific to the LSP's or the FSO's individual planning schemes are not considered for brevity. The baseline settings used in the presented experiments are $\Delta t = 1$ and two rounds of communication, denoted by $N^{\text{com}} = 2$.

The total cost of the implemented actions (the realized cost) is lower when decision epochs are every 0.6 h under the transport paradigms that allow replanning as can be seen in Fig. 10. The optimal replanning interval under intermodal transport is longer, namely 1 h. This is expected, as intermodal transport can combine requests better when more requests are considered simultaneously. However, when planning only happens every 2 h, requests that could have been picked up before the decision epoch ends up being delivered too late. Compared to $\Delta t = 1$, $\Delta t = 2$ results in a 178% increase in lateness hours (TEU-h) on average between the repetitions

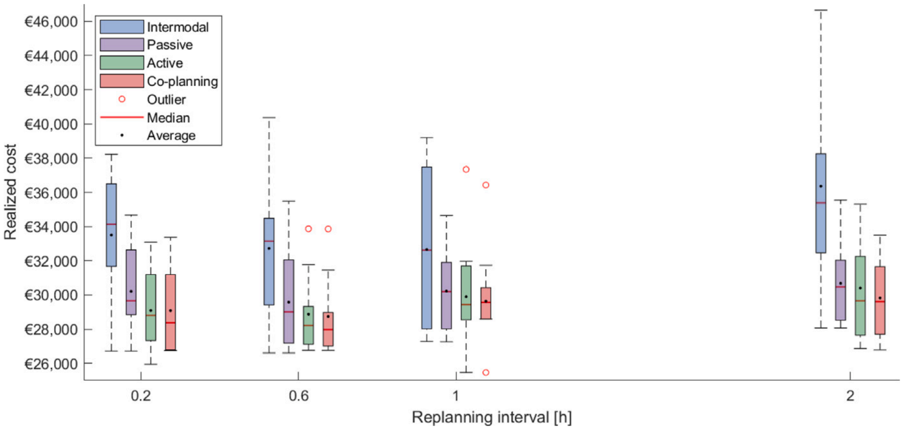

Fig. 10. The impact of the replanning intervals (in hours) on the realized total cost.

of the experiments with different requests. A large portion of lateness is related to the scarcity of trucks as the modal split for road transport only increases slightly to 16.16% compared to $16.02 - 16.07\%$ when the decision epochs are more frequent.

The realized transport cost is generally better when old plans are reconsidered. The total realized cost under co-planning is on average 0.3% lower than under active synchromodal transport, which in turn is 2.01% lower than under passive synchromodal transport. Under all three paradigms, the fees paid for late delivery are between 8% and 11% of the total realized cost with the lowest parts at $\Delta t = 0.6$. Disregarding the fee for late delivery, the average realized cost (the cost of transport) is the lowest for $\Delta t = 0.2$, indicating that frequent decision epochs lead the parties to commit to actions that soon are found to be suboptimal. Interestingly, the average cost of road transport is the lowest when $\Delta t = 2$ under active synchromodal transport and co-planning despite there being no noticeable pattern in the modal split for road transport, which indicates a more efficient routing of trucks to decrease the time they run empty.

The improvements gained from co-planning and additional rounds of communication highly depend on the shipment requests. The cost reductions by using co-planning are as high as 10.6%. The largest reductions are found when co-planning is used instead of active synchromodality, corresponding to the shift from one to two rounds of communication. Cost reductions are possible for all request sets with the right combination of the interval between decision epochs and the number of rounds of communication (two to four rounds). There was no clear correlation observed between the volume and delay fee profiles of the request sets and the resulting realized cost. The results for one request set (set 8) stand out. Here, co-planning increased the realized cost by 5.1% compared to active synchromodality, with additional minor increases for additional rounds of communication when decisions are taken every 0.6 h. When decisions are taken every 2 h, co-planning decreases the total cost by 2.0% for the same request set, while additional rounds of communication increase the cost up to 3.5%. Excluding this request set, the trend is that co-planning results in more consistent realized costs than active synchromodality, and that additional rounds of communication have a minor impact, as seen in Fig. 11. The average realized cost decreases a bit with co-planning and in most cases, the median realized cost decreases as well. Similar patterns are found when comparing the total distance driven by the trucks (full and empty), as seen in Fig. 12. As shorter distances often correspond to lower emissions, this improvement is worth noticing. The variations between different request sets are large, which is partly due to the fact that the volume transported by the FSO compared to scheduled services varies from 11% to 25%.

To test the computation time of different transport paradigms, we design 12 scenarios with different method parameter settings. We replicate each case 10 times to report the average values. We use the CPU to represent the maximum computation time per decision epoch for each case. The CPU must be lower than the replanning interval to ensure enough time for computing a plan. Fig. 13 shows that the maximum CPU is 50 s while the minimum setting of replanning interval is 0.2 h (equal to 720 s). Therefore, with the proposed approach, the time is always enough to obtain optimal solutions.

6.3.2. Sensitivity to scenario parameters

The performance of transport planning is influenced by the nature of the transport system. This section describes how co-planning and the benchmark methods perform when the truck fleet sizes, the shipment request lead times, and delay fees differ from the base scenario. These parameters can be influenced by either the LSP or the FSO at a tactical level, but are seldom controllable in daily operation. In all experiments, the method parameters are $\Delta t = 1\text{h}$ and $N^{\text{com}} = 2$.

When the truck fleet is small, road transport is not readily available. As seen in Fig. 14, the average realized cost decreases with an increasing fleet size for both co-planning and the benchmark methods except when the fleet size is 30. At this fleet size, co-planning performs slightly worse than when 25 trucks are in the fleet. When the fleet gets larger, the average truck driving distance (empty and full) generally increases with a few exceptions for active synchromodality and co-planning for a fleet size of 25 and above. The ability to replan has a large impact on all fleet sizes. Intermodal transport not only results in the highest average costs for small fleets, the level of dependency on the shipment request set is also higher (the variance of the results). Active synchromodality and

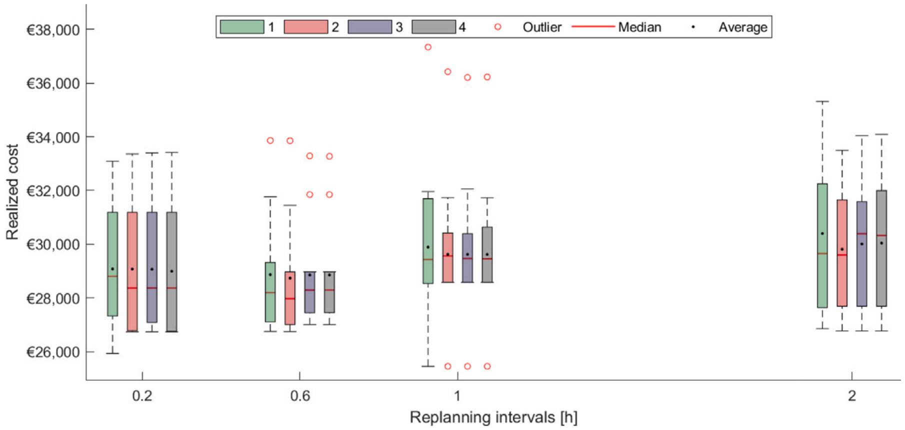

Fig. 11. The combined impact of replanning interval [h] and number of communication rounds on the performance of co-planning in terms of realized cost.

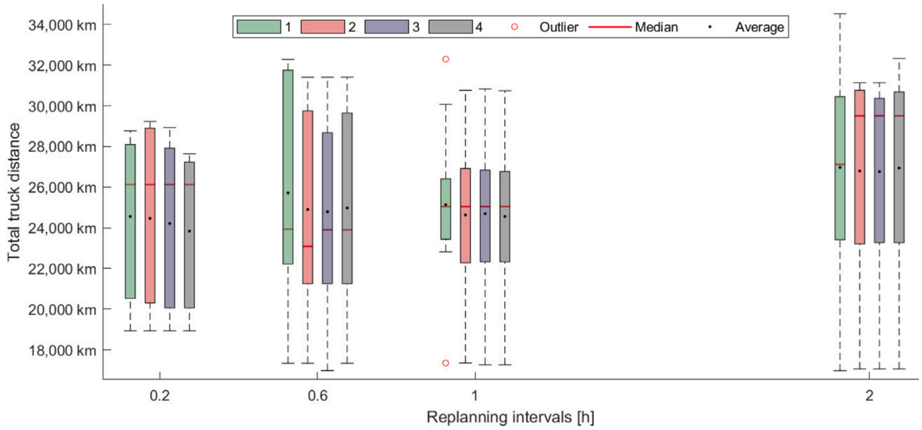

Fig. 12. The combined impact of replanning interval [h] and number of communication rounds on the performance of co-planning in terms of the distance driven by the trucks. Notice the modal split for trucks varies between 11% and 25%.

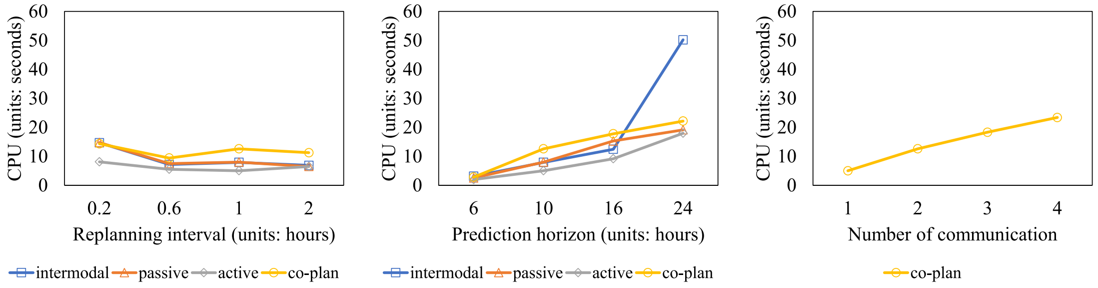

Fig. 13. The computation time of transport paradigms under different parameter settings.

co-planning outperform passive synchromodality on the average on all truck fleet sizes, and in most co-planning results in lower realized cost than active synchromodallity. This confirms that the ability to take frequent decisions improves the realized plans. The improvements stemming from communications are the largest when 5 trucks are in the fleet and are largely tied to a 16% decrease in the distance driven by the trucks.

The time between the release of a shipment request and their deadline highly affects the cost of operating the transport system, as seen in Fig. 15. In the figure, the standard lead times for the shipment requests are as described in Section 6.1, for short lead times, the arrival times of the shipment requests were adjusted so the lead time of each request became half of the original time. For long lead times, the arrival times were adjusted to 150% of their original length. Intermodal transport incurs the highest costs for all lead time lengths with the most request-sensitive results (largest spread). When the lead times are short, active synchromodal

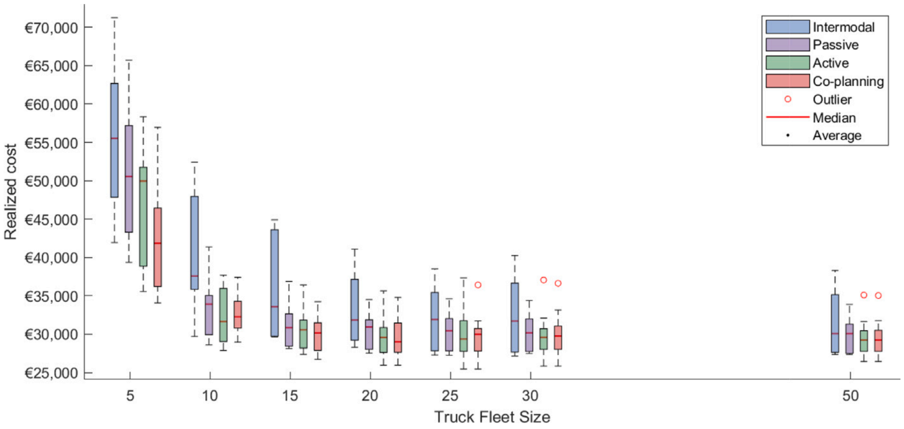

Fig. 14. Impact of the truck fleet size.

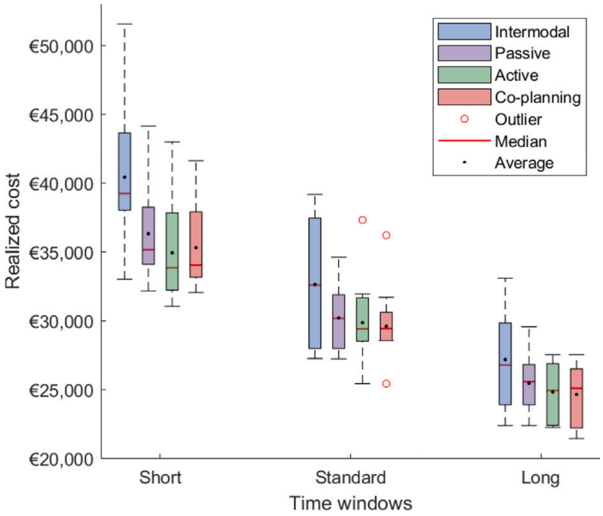

Fig. 15. Impact of shipment requests' lead times.

transport performs better than co-planning while co-planning outperforms active synchromodality for long lead times. This is due to the communication mechanism resulting in a lower bound for departure time, which in combination with the LSP's fixed estimation of travel time shifts the optima and limits the search space away from solutions with delayed delivery. Under active synchromodal transport, the actions towards the late deliveries will be taken and possibly corrected later, while the communicated lateness under co-planning causes the LSP to change to plans with lower delays. For scenarios where delay fees are unavoidable, the implemented plans under co-planning may still be infeasible as only limited information is communicated in each round. The realized cost of the finally chosen plan may thus be worse than the realized cost of the initial plan. It is worth noting that the magnitude of the cost increase in proportion to the total realized cost is very high. When the lead times are long, the effect of delay penalties is less and the information received in co-planning can be better utilized.

Delays are sometimes penalized explicitly, but implicit consequences such as loss of trust are hard to quantify exactly. In the performed experiments, it is assumed that the fee for late delivery is tied to the lead time between the release and delivery date of a shipment request. Requests with tight lead times are considered to have a total delay fee (explicit and implicit) that is higher than those having more time to perform the transport. To assess the sensitivity of co-planning and the benchmark methods to the quantification of implicit delay fees, experiments with a wider and a narrower spread in delay fees were performed. The impact of this variation was modest as seen in Fig. 16. The standard delay fee is 5, 10, or 15 as described in Section 6.1. A tight delay fee denounces scenarios where the delay fees of the shipment requests are adjusted to 7.5, 10, and 12.5 depending on the lead times in the same fashion as for the standard delay fee. On the other hand, a broad delay fee indicates an adjustment to 2.5, 10, and 17.5. The results confirm that replanning produces the largest cost improvements and communication decreases the realized costs further.

In conclusion, if decisions can be taken very frequently for shipment requests with short deadlines with a high likelihood that trucks are available, then active synchromodal transport performs well in terms of the total realized cost. If the scenario is more

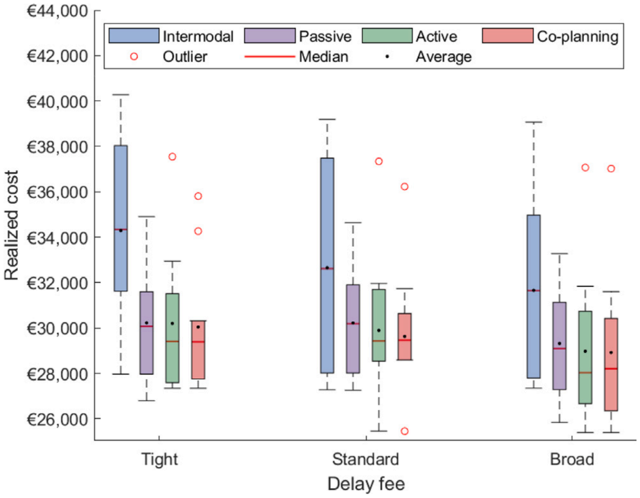

Fig. 16. Impact of the delay fee.

complex, with fewer decision epochs, larger flexibility in when containers are moved, and more scarcity of vehicles, then co-planning performs better. It appears that communication improves the repositioning of trucks, resulting in a more sustainable road-network operation, but as the feedback is limited to expected arrival times, some of the benefits are reduced by the LSP's lack of knowledge regarding the actual cost of including road transport. As the LSP optimizes with a fixed cost of transport per container between given locations, the synergies between future repositioning of empty vehicles and upcoming requests are only partly utilized. The results for all methods are highly dependent on the details of the request set.

7. Discussion and managerial insights

In the previous section, numerical results were provided that show the performance of the proposed co-planning framework compared to three frameworks under intermodal and synchromodal transport paradigms. The results are generated for a limited number of scenarios, but do provide interesting insights about the strengths and weaknesses of each framework:

- Intermodal:
  - – Very sensitive to alignment between shipment requests and schedules of services like train and barge. The variation of the results is the highest in most experiments.
  - – Worst performance on total cost even when shipment requests are well aligned with the schedules. A large part of the total cost is from the cost of delayed delivery.
  - + Simple communication with shippers and other stakeholders as only timing changes.
- Passive synchromodality
  - – Performs second-worst in terms of total cost in most experiments.
  - + Relatively simple communication with shippers and other stakeholders as changes only happen when original plans are infeasible.
- Active synchromodality
  - – Synchromodal contracts are necessary as changes are frequent.
  - + Performs better than passive synchromodal framework in most experiments.
  - + Performs well when lead times are short.
- Co-planning
  - – Synchromodal contracts are necessary as changes are frequent.
  - – Feedback has to be communicated and reflecting it increases the time it takes to make a plan.
  - + Compared to active synchromodality, shorter distances are driven by flexible vehicles even when it is not a direct part of the objective.
  - + Performs better than passive synchromodal framework in most experiments.
  - + The least sensitive to the alignment between requests and schedules in most experiments.

Based on the identified strengths and weaknesses and the sensitivity analysis of the four transport paradigms, we provide the following managerial insights:

1. Close attention needs to be paid to the alignment between shipment requests, schedules of services, and truck fleet sizes in order to reach a good transport performance.
2. Flexibility is crucial when there is variation in the alignment between shipments and the transport network setting.
3. Communication and co-planning should be prioritized when making the right decisions is more important than making quick decisions, e.g., when the truck fleet size is very small or replanning intervals are long.
4. One round of feedback, in most cases, provides sufficient improvement in total costs.

Co-planning using the proposed or other frameworks has the potential to create better alignment between the plans of different stakeholders. It performs better than the passive synchromodal framework, which in turn significantly outperforms the more traditional intermodal transport framework. In some situations, the proposed co-planning framework improves the cost of transport compared to the active synchromodality framework, while in other situations, the reverse is true. The main limitation of the proposed co-planning framework is that it slows down decision processes, as feedback needs to be reflected. Furthermore, the proposed co-planning framework is likely to provide less favorable solutions than the described decentralized active synchromodal framework when making a quick decision is better than making the right decision, that can especially be seen in the sensitivity to lead times, but also in the sensitivity to truck fleet sizes. In other words, communication and co-planning become more critical when there is not much room to frequently update the decision during the planning process. For most small truck fleet sizes, co-planning performs better as a solution closer to the global optimum is more beneficial. Only in the case with 10 trucks, active synchromodality performs better as in that case, there are sufficient trucks to be able to correct the sub-optimal solutions later in the process. The main advantage of the proposed co-planning framework is the ability to avoid infeasible plans in time. This is especially visible when decision intervals are long, lead times are long, or the vehicle fleet size is very small.

Synchromodal transport is a very recent way of organizing transport. There are still many hindrances within the industry, but also within the assumptions held by researchers. Most notable one is the need to frequently align plans between multiple stakeholders to gain the potential benefits in terms of cost, system resilience, and other prioritized indicators (e.g., emissions reduction). Co-planning builds on the same assumption and adds the need for frequent communication of plans. With increasing levels of digitalization in the transport industry, frequent communication becomes more available and, for companies that prioritize it (e.g., within the consumer-focused cold chain), it is an already implemented way of improving the profitability of the transport services.

For co-planning to become widely implemented in open transport systems, reward structures for data-sharing or profit-sharing have to be in place. Co-planning does not change the decision power of individual stakeholders and it emphasizes that the shared information is bounded, well-defined and shared at realistic intervals. Co-planning can be seen as a step on the way to distributed transport systems where the alignment between stakeholders often is closer to optimal, but where the data exchange is demanding and not always clear for the involved stakeholders. Co-planning can also be seen as a middle-way between a system-optimal operation of transport systems and a competitive market.

8. Conclusions and future research

This paper investigated a decentralized container transport system with two decision-makers: a logistics service provider (LSP) that decides the mode and route choices of shipment requests over a multimodal network, and a flexible service operator (FSO) that decides vehicle routes for flexible services to fulfill the transport requests proposed by the LSP. A mixed integer linear programming model was developed for the LSP's optimization problem and a model predictive control method was developed for the FSO. Thanks to the development of information technologies, the real-time position of containers is tracked by the LSP and the real-time position of flexible vehicles is available to the FSO. This paper designed a synchromodal framework to control the decision process that allows mode and route changes based on real-time information. Thanks to the development of communication technologies, stakeholders are able to communicate with each other in real-time, but they need reasonable ways of information exchange without compromising their autonomy. This paper developed a co-planning method under the synchromodal framework that entails communication between the LSP and the FSO in terms of transport requests' estimated arrival times. A case study and extensive numerical experiments were conducted to verify the performance of the synchromodal paradigm with co-planning in comparison to three benchmarks: an intermodal paradigm that does not allow mode and route choice, a passive synchromodal paradigm that adjusts mode and route choice when disturbances happen, and an active synchromodal paradigm that updates transport plans at fixed time points without information sharing among stakeholders. The experimental results showed that in all scenarios with different parameter settings, synchromodal paradigms perform better than the intermodal paradigm in total costs and truck utilization rate. Decision-makers (e.g., container transport operators) need to motivate shippers to change from fixed-mode booking to flexible-mode booking. The active synchromodal paradigm performs a little better than the co-planning paradigm in scenarios with short lead times and lower delay penalties while co-planning performs better for long lead times and higher delay fees.

In this paper, the co-planning method relies on the communication of transport requests' expected arrival times which might become inaccurate caused by dynamic requests and traffic conditions. Future research could consider that the FSO additionally updates the LSP about the expected arrival times during the transport. This is relevant both with respect to travel times longer than the planning horizon and if scenarios with travel time uncertainties are considered. Besides, another type of co-planning contract could be investigated, which specifies that the FSO should not truck anything that cannot meet the delivery time set by the LSP, or that violates that deadline by more than a given period of time. This tactical decision may have a considerable impact on the performance of the transport system, so a thorough study of possible contract types and their consequences for the co-planning methods is an interesting future research direction. Another interesting avenue is embedding the use of incentives into the co-planning contracts. This could be allowing delay fees to be updated during transportation by the LSP to indicate changed prioritization or real-time communicated discounts on flexible services that fit with expected empty legs in the FSO's routing plans. Research on transport systems with multiple, competing stakeholders or the possibility to reject or use external services for certain requests comprise an additional interesting direction for future research. Furthermore, to better reflect the restrictions faced by practitioners, future research could incorporate time constraints and location restrictions for trucks. This could allow for modeling drivers ending their work period at certain locations and driving rest regulations.

CRediT authorship contribution statement

Rie B. Larsen: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Wenjing Guo:** Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Bilge Atasoy:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Data availability

Data will be made available on request.

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Appendix. Notation

Mathematical operators	
$\lceil \cdot \rceil$	Round up to nearest integer
$\lfloor \cdot \rfloor$	Round down to nearest integer
Method parameters	
t	Time
Δt	Time intervals between decision epochs
δt	Time interval used to discretize time in the FSO's plans
k	Counter for decision epochs in the LSP's plan
κ	Counter for discrete time steps in the FSO's plan
T_p	Planning horizon for the FSO
M	Large (enough) numbers used for binary constraints
$N^{\text{simulation}}$	Length of a simulation
Sets	
N	Terminals
R	Shipment requests from shippers to LSP
$\mathcal{R}$	Transport requests from LSP to FSO
S	Transport services, $S = S^{\text{scheduled}} \cup S^{\text{flexible}}$
S_i^+	Transport services depart at terminal $i \in N$, $S_i^+ = S_{i^+}^{\text{scheduled}} \cup S_{i^+}^{\text{flexible}}$
S_i^-	Transport services arrive at terminal $i \in N$, $S_i^- = S_{i^-}^{\text{schedu}} \cup S_{i^-}^{\text{train}} \cup S_{i^-}^{\text{truck}}$
H	Hubs and terminals in the flexible mode's network, $N \subseteq H$
H_i	Set of nodes reachable from node i by flexible service
Network parameters	
TD_s	Departure time of service $s \in S^{\text{scheduled}}$
TA_s	Arrival time of service $s \in S^{\text{scheduled}}$
c_s	Transport cost of service $s \in S$ per container
τ_{ij}	Traveltime by flexible service from node $i \in H$ to node $j \in H$

Shipment requests parameters	
o_r	Origin terminal of shipment request $r \in R$
d_r	Destination terminal of shipment request $r \in R$
q_r	Container volume of shipment request $r \in R$
t_r^{release}	Release time of shipment request $r \in R$
t_r^{due}	Due time of shipment request $r \in R$
c_r^{delay}	Penalty cost coefficient of request $r \in R$ per container per hour overdue
Logistics service provider variables	
x_{rs}	A binary variable equal to 1 if request $r \in R$ is matched with service $s \in S$, 0 otherwise
t_{ri}	Arrival time of request $r \in R$ at terminal $i \in N$
t_{rs}^{depart}	Departure time of flexible service $s \in S^{\text{flexible}}$ with request $r \in R$
t_r^{delay}	Delay of request $r \in R$ at destination terminal d_r
LB_{rs}	Departure time lower bounds of flexible service $s \in S^{\text{flexible}}$ with request $r \in R$
Flexible service operator parameters	
ω_{ij}^{t}	Cost of driving flexible services from i to j
ω^{s}	Cost of stacking one container at a node which is not its destination
γ	Capacity of the flexible service
Flexible service operator variables	
$\xi_{rij}(k)$	Number of containers from request r departing from location $i \in H$ at time $t + k\Delta t$ on a flexible vehicle towards location $j \in H$
$\chi_{ri}(k)$	Number of containers from request r stacked at location $i \in H$ at time $t + k\Delta t$
$\upsilon_{ij}(k)$	Number of flexible vehicles departing terminal i at time $t + k\Delta t$ traveling to location j

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