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A B S T R A C T

Hinterland freight transportation is managed according to a pre-designed schedule. In daily operations, unexpected uncertainties cause deviation from the original plan. Thus replanning is needed to deal with the perturbations and complete the transportation tasks. This paper proposes a mixed-integer programming model to re-plan hinterland freight transportation, based on the framework of synchromodality. It is a holistic resolution of shipment flow rerouting, consequence transshipment organization in the intermediate terminals, and corresponding service rescheduling. The replanning benefits from a high operational flexibility and coordination via a split of shipment and aligning the departure time of service flows with the shipment flows.

1. Introduction

Hinterland freight transportation is carried out in accordance with an elaborated tactical plan. A service Network Design (SND) problem lies at the core of the tactical planning process, addressing issues like the selection and scheduling of services, specification of terminal operations and routing of shipment flows (Crainic, 2000). These plans are designed on the basis of predicted freight volume. Stochastic and robust planning are studied extensively to prevent or limit the influence of prediction bias.

At the operational level, the tactical schedules are implemented on a local scale with a shorter time window. During this process, the transportation network is vulnerable to uncertainties and variations. Those not only rise from the external environment (unexpected additional or cancelled freight demands, weather caused hazards, delays of the shipment release), but can also internal from system fluctuations (congestion, breakdown and human-caused malpractices). The stochastic or robust planning plan is unable to handle all unexpected scenarios in everyday practice. It is still on open filed to regulate uncertainties at the operational level.

Synchromodal transportation is an upcoming new solution succeeding intermodal transportation towards a more flexible and cooperated freight transportation (Tavasszy et al., 2010) at operational level to deal with uncertainties. Under the framework of synchromodality, shippers accept a mode-free booking and only determine the price and quality requirements (Behdani et al., 2016). The involved service providers collaborate under the centralized supervision of one Logistic Service Provider (LSP) (see also SteadieSeifi et al., 2014; Li et al., 2017 and Pérez and Mes, 2017). This implies that it is possible to perform real-time switching among different modes (Behdani et al., 2016).

The centralized LSP holds the promise of generating specific replanning solutions to the specific uncertainties encountered in each individual case. The replanning questions come in: (1) Which part of the original SND plan can be re-planned? (2) To what degree can the re-planning solutions deviate from the SND plan? As mentioned above, the SND mainly consists of three components: the

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shipment route choices, the terminal operations, and the service schedules. With regard to the first component, it is important to deliver shipments to their destinations on time. Hence, complete flexibility can be given to the shipment route replanning. This is under the agreement of mode-free booking and real-time switching. The thorough re-routing of shipments unavoidably involves the replanning of terminals operations and services schedules. Those can be integrated in the replanning and benefit from the co-operation of all synchromodality operators.

This replanning model further carries out two consecutive synchronization tasks: to derive the corresponding transshipment flows at the terminals, and to synchronize the service rescheduling with the shipment rerouting. A dilemma emerges for to the LSP while rescheduling the LCS. The higher degree of flexibility given, the more flows can be diverted from truck services to LCS. However, that will also generate higher costs as a result of deviating from the SND plan (paying for cancellations or postponing services) and retrospective re-positions. The trade-off between flexibility and deviations is crucial for the rescheduling of LCS. This work explores how LSP can synchronize these intertwined tasks for hinterland freight transportation replanning.

This study includes the following contributions to existing research. We construct a model that regulates the shipment flow re-routing and services re-scheduling. It can be used for a hinterland freight transportation network under the framework of synchromodality. The shipment rerouting is given a higher degrees of freedom, involving the split and bundling of shipments. Consecutively, the transshipment flows at the intermediate terminals are extracted from the shipment flow rerouting. Transshipment is an important link in the overall process, albeit one that is sometimes neglected and over-simplified in some studies. Last but not least, moderate flexibility is given to the operating times of services, to be synchronized with the shipment flows. Alignment is introduced to LCS, i.e., the barge and rail services are given a buffer time that transcends the scheduled time. Thus shipment flows *en route* can be shifted from truck services towards LCS.

The model can be used for daily planning at the operational level. It can be embedded as the 'real-time layer' of the SYNCHRO-NET service platform (see Fig. 2 of Giusti et al., 2019). In this paper, the model is tested in the Rotterdam hinterland transportation network, in cases involving late release of shipments, latency of LCS, volume fluctuation of shipments, and a variety of mixed perturbations. The model can provide a replanning resolution within seconds. In addition, we compare this model to other rigid replanning methods. The results show that the proposed synchromodality replanning model can save more overall operating costs, improves the modal split of barge and rail services, and improves LCS utilization. Finally, the model is tested with theoretical instances, with different network sizes, shipment amount and network typologies, providing that the model is able to solve small-size problems efficiently.

The remainder of this paper is organized as follows. The next section provides a review of relevant studies those incorporate uncertainties in transportation planning/replanning. The problem is formally described in Section 3, and presented mathematically in Section 4. The mathematical model describes the synchronization scheme of shipment re-routing, transshipment flows at the intermediate terminals and service rescheduling. The replanning algorithm is calibrated and described in Section 5. Section 6 tests the proposed model in the Rotterdam hinterland network with a variety of perturbations, with the solutions being provided tailored to the specific situations. The model is further analyzed in Section 7 in three aspects: (1) critical path and re-scheduling flexibility; (2) comparison with other two rigid replanning methods; (3) theoretical instances to check the solving difficulties. Finally, in Section 8 we present our conclusions and discuss possible avenues for future research directions.

2. Literature review

In this section, we take a look at the studies which deal with unexpected fluctuations in freight transportation planning. The studies discussed here can be divided on the basis of the uncertainties (also called perturbations) involved.

Uncertainties in freight transportation can rise in exogenous and endogenous form. Exogenous uncertainties mainly come from the shipments, in the form of volume fluctuations, release date deviations, and the corresponding mutual impact. Endogenous uncertainties are usually time-dependent, such as longer travel times due to congestion, late arrivals of services, and late releases of empty containers. Both exogenous and endogenous uncertainty studies can be divided further on the basis of the planning horizon, i.e., the tactical, operational, and mixed tactical-operational level. In practice, the planning is sometimes crossed, resulting in mixed tactical-operational level problems. Table 1 provides an overview of the corresponding literature.

The emphasis of this review is on the types of uncertainty and the corresponding solution methodologies. As such, some of the studies discussed here concerns single mode transportation or supply chain logistics. For a more detailed review of multimodal freight transportation, see SteadieSeifi et al. (2014).

2.1. Exogenous uncertainty

Shipment stochasticity is the group of exogenous uncertainties has been studied the most. It is mainly addressed from the level of tactical planning. Usually, the shipments are assumed to have a known probability distribution. And the prevention or mitigation plan is modelled and solved via a two-stage approach. The first stage is formulated as a deterministic network flow planning (NFP) or service network design (SND) problem. And the uncertainties are integrated in the following stage via stochastic programming or *robust optimization*.

Lium et al. (2009) studied shipment volume stochasticity (including volume, and release date) in the SND problem. The continuous distributed stochastic volume was approximated by scenario generations, and handled by outsourcing the unexpected shipment to other service providers. Based on the work by Lium et al. (2009), Hoff et al. (2010) developed a variable neighbourhood search-based approach to solve a large-scale SND problem with shipment volume stochasticity. Bai et al. (2014) extended the work

Table 1
Literature of studies dealing with uncertainty.

	literature	Uncertainty	Planning level	Modes	Routes	Shipment split	Transshipment	Solutions
Exogenous	Lium et al. (2009)	shipment	t	H	p	✓	-	outsourcing
	Hoff et al. (2010)	shipment	t	H	p	✓	-	outsourcing
	Bai et al. (2014)	shipment	t	H	p	✓	-	outsourcing and services' itinerary re-planning
	Meng et al. (2012)	shipment	t	B	a	-	-	changing ship size
	Pérez Rivera and Mes (2017)	shipment	t-o	B,R,T	p	-	-	picking up date re-planning
Endogenous or mixed	Andersen and Christiansen (2009)	transit time	t	R	p	-	-	-
	Clark and Watling (2005)	transit time	t-o	T		-	-	-
	Escudero et al. (2013)	transit time	t-o	T		-	-	shipment flow re-assigning
	Goel (2010)	transit time	t-o	R,T	p	-	✓	shipment flow reassigning
	Li et al. (2015)	mixed	t	B,R,T	a	-	-	shipment flow reassigning
	van Riessen et al. (2015)	mixed	t-o	B,R,T	p	✓	✓	shipment flow reassigning

Note: Modes: B: Barge, R:Rail, T: Truck. H: homogeneous, not mentioned which one;
Planning level: t: tactical level planning, t-o: mixed tactical and operational level;
Routes: p: path level; a: arc level.

with an extra solution of itinerary re-planning, i.e. adjusting the service itinerary of services. Meng et al. (2012) proposed to handle the seasonal shipment uncertainty by deploying different amounts and sizes of ships for a liner ship fleet management. We note that each of the above mentioned studies considered homogeneous services within the network.

Researchers also handle uncertainty in SND through robust optimization as an alternative to stochastic programming,. Ukkusuri et al. (2007) proposed a robust SND model in which the service network was designed to be less sensitive and more resilient to shipment uncertainty. Atamtürk and Zhang (2007) described a two-stage robust optimization strategy by deferring a subset of shipment decisions to the second stage, i.e. deciding after the realization of uncertain shipments. List et al. (2003) proposed to include the option of declining unexpected shipments. If an accepted shipment exceeded the service capacity, then the model allowed the service provider to choose a different fleet size. We emphasize that the robust optimization literature discussed also dealt with homogeneous service modes.

The stochastic programming (Lium et al., 2009; Hoff et al., 2010 and Bai et al., 2014) is a considerable step towards incorporating the effect of uncertainty into tactical programming. However, it should be pointed out that outsourcing the shipment flows, as proposed in those studies, is not a good way to address unexpected shipments. Because the service provider loses business to competitors and the operational costs involved are expensive. On the other hand, the solution of robust optimization handles the uncertainty by providing additional service capacity or buffer time at critical nodes and links, (see Ukkusuri et al., 2007). It would appear that the solution obtained via robust optimization requires higher investment. Both stochastic programming and robust optimization result in a deterministic solution that obviously is not able to deal with all possible uncertainties occurring in real practice.

The work by Pérez and Mes (2017) presents one of the early studies aimed at solving the shipment uncertainty within the framework of synchromodality. They assumed the LSP possesses the probabilistic knowledge of the shipment and will gradually know the probability over time. The problem was settled using look-ahead planning, i.e., deciding to pick up the shipment directly or postpone. Since Pérez and Mes (2017) concerned the day to day planning, some details were overlooked. For example, the model did not deal with the operating schedules of services and related transshipment connections.

2.2. Endogenous uncertainty

Among the endogenous uncertainties, transit time (or travel time) is the one that is studied the most. It is usually affected by congestion, weather conditions and other time-dependent factors. As such, it is addressed mainly at the operational level or mixed tactical-operational level.

Some studies focus on quantifying the transit time uncertainty. Andersen and Christiansen (2009) included transit time uncertainty in the SND problem of a railway network. They directly converted the consequence of the time uncertainty to unit flow cost and quantified the impact of uncertainty on service quality. Clark and Watling (2005) proposed a way to estimate the probability distribution of the transportation time for a road (truck) network. These studies focused on quantifying the uncertainty and did not discuss possible resolution approaches.

Goel (2010) quantified the influence of transit time visibility for a road and rail network, adjusting the shipment routing according to the transit time uncertainty. He concluded that the on-time delivery performance could be improved by increasing the visibility of the travel time uncertainty. Escudero et al. (2013) suggested a dynamic approach to solve the transit time uncertainty for a daily drayage problem. To handle the changed condition, the model reassigned the shipments on condition of real-time knowledge of the trucks' location.

The studies discussed above deal exclusively with one sort of uncertainty. However, in reality, the network can experience multiple uncertainties. Li et al. (2015) integrated shipments uncertainty and highway travel time uncertainties into the NFP problem. They calculated the truck travel time based on the density of truck flows on the highway. The following NFP planning dealt with the uncertainty under a cooperative mechanism among different service providers. Note that the due time requirements for shipments were not provided in this study.

At the same time, delays (high frequency, low impact) or disruptions (low frequency, high impact) are inevitable in any transportation network. There are very few studies that examine how to deal with delays or disruptions and recover the network in the domain of multimodal freight transportation. van Riessen et al. (2015) presented one of the very few management strategies for intermodal networks. Their approach involved a dynamic SND planning using the updated information of available services and remaining shipments tasks. No new approaches were introduced in replanning stage, including rerouting, re-assignment or itinerary replanning. As such, a proper model of flexible management that can handle the deviations from the original plan at the operational level has still not been proposed.

To summarize, most existing studies from the tactical level mainly address shipment uncertainty for single-mode networks. Their main aim were to mitigate the effect of uncertainties in advance. The Dynamic SND, at mixed tactical-operational level, can capture some time-dependent uncertainty. However, although it is a step up from the deterministic programming, how to carry out a re-planning to deal with any unexpected uncertainty for a multimodal network still remains a question. Meanwhile, there are pervasive studies focusing on re-planning in public (passenger) transport systems and (passenger or mixed passenger and freight) railway systems, just to name some, Binder et al. (2017) and Corman et al. (2017a). Those studies provide useful ideas on how to handle uncertainty at the operation level, including the rescheduling of the services, itinerary or local-itinerary replanning. There is an important difference between passenger transportation and freight transportation: freight flows are under full control. Thus, one significant solution can be obtained from the flow assignment replanning. Synchromodality adopts book-free booking and a centralized LSP organization, which enables a timely mode-switch among different service modes. As such, synchromodality provides a cornerstone for the flexible management of possible uncertainties at the operational level.

Based on the aforementioned literature study and the development of synchromodality, we propose a model for freight transportation at the operational level. It can be used for daily planning, or serve as a 'shuttle/transaction plan' for the time window after disturbances occur and before returning to the regular plan. The proposed model uses the tactical planning as input to formulate the flow assignment re-planning and service rescheduling. Note that the model does not include major disruptions. Here it is assumed that the terminals and roads are capable to continue the services.

3. Problem description and assumption

Consider a synchromodal network engaged in transporting shipments (or freights) from many origins to many destinations, using various service modes. Our model implements the re-planning of involved operators to cope with uncertainties at the operational level.

Let N denote the set of nodes of the network, standing for terminals which can be ports, railway stations or truck hubs. Mark each service by a sequence number $v \in V$. The arc (also named as link or leg) $a \in A = (i, j, v)$ indicates a service v from terminal $i \in N$ to another one $j \in N$. Thus the physical transportation network can be represented as a hyper graph $G(N, A)$.

A service v is described using an attributes tuple $(m_v, u_v, f_v, \psi_v, p_v)$. The first entry m_v denotes the service mode, which is either a barge, rail, or truck; u_v is the capacity of the service; f_v represents the fixed cost as long as the service is used. ψ_v refers to cancellation costs, applicable to the situation where a pre-planned barge or rail service v is not used in the replanning; p_v is the itinerary of the service, which is pre-specified from the SND plan.

An arc a is regulated with the tuple $[\pi_a^{\text{dep}}, \pi_a^{\text{arv}}, k_a, c_a]$. Remind that for the rail and barge services, tactical planning pre-specifies the itinerary, frequencies, departure times and corresponding arrival times. π_a^{dep} and π_a^{arv} represent the pre-plan the departure time and arrival time. k_a is the required traverse time and the variable cost of using this arc. c_a is the unit cost of the container transportation, which will be used in combination with the load volume.

Here we distinguish the arc $a = (i, j, v)$ and the service v. There can be parallel arcs between two terminals if that region contains more than one service. Meanwhile, the service's itinerary p_v can cover more than two terminals, i.e., $\|p_v\| \geqslant 2$. The order of an element $i \in p_v$ is marked as $q_{i,l}$; The itinerary and frequency (or fleet size) of LCS remain the same as the original plan in this study. However, an additional buffer time ϕ_a^{dep} is introduced to reschedule the departure time of services. Consequently, the real departure time of LCS are regulated between the range $[\pi_a^{\text{dep}}, (\pi_a^{\text{dep}} + \phi_a^{\text{dep}})]$.

In a similar way, we characterize each shipment $s \in S$ by $(n^s, d^s, \alpha^s, \beta^s, \gamma^s, [\rho^{s,-}, \rho^{s,+}])$. Here s is a load of containers, with the volume denoted as n^s, to be transported from the same origin node o^s to the same destination node d^s. Each s has a release time α^s at

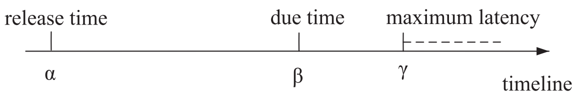

Fig. 1. Release time, and delivery window of one shipment.

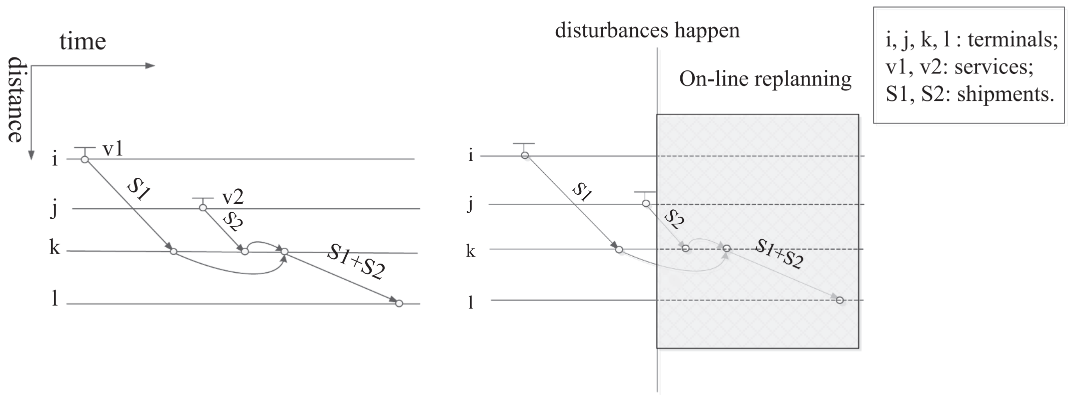

Fig. 2. Initial Service schedules and Online planning after disturbances.

the origin and expected due time β^s at the destination terminal, as shown in Fig. 1. Both early and late arrivals are allowed, where the early arrival is charged via the storage costs $\rho^{s,-}$, while a delay penalty $\rho^{s,+}$ is incorporated due to a decrease of service quality. The arrival time of each commodity can not exceed the pre-set maximum latency, noted as γ^s.

In daily operation, various sources of disturbances inevitably cause perturbations to the pre-specified transport operations. We define the state of a system as disturbed if: any shipment s is released later than α^s at the origin, any pre-specified service v is broken down, any v which carries shipment(s) experiences a late departure or arrival, any arc a is known to be in congestion or blockage and will lead to longer transit time, or a combination of some of those situations.

Possible influences can be: broken connection of the shipments on the way, violation of the due time, a large increase of in operational costs, etc. In this situation, LSP can use our model for short-term online replanning, to deal with the occurred disturbance (s) and complete the transportation of the shipments. As shown in Fig. 2, the replanning will be conducted directly after the delays, using the updated information of services and the shipments. Moreover, the system goes back to normal once the aforementioned situation has been solved and the transportation network can operate as originally planned.

Remind that under the framework of synchromodality, all service providers work together under the centralized organization of LSP. Perboli et al. (2017) studied the collaboration of the stakeholders from the business perspectives. Our model is build based on the assumption of this collaboration. For the synchromodal re-planning, we only consider shipments those have already been accepted. This means no new shipments will be accepted during the replanning. Rather than accepting new shipments and generating new revenue, it is more rational to finish existing shipments and to avoid the penalty of delayed or failed delivery. Finally, the updated information about the real-time locations of services is assumed to be available. Based on the full deterministic information, the resultant model will be optimized for one single stage. This open-loop control avoids the issues involving the consistency of solutions across different stages, which is the inherent problem of closed-loop control (multi-stage planning).

We assume that cancelling certain pre-planned services is feasible with cancellation costs when the services are quite sufficient for the shipments. Meanwhile adding extra services or changing pre-planned routes lie beyond the scope of this study.

4. Mathematical formulation

The aim of this section is to construct an integrated and detailed model of the shipment flow assignment replanning and real-time deployment of the service fleet. We model the online replanning in three parts. (1) the shipment flow re-planning for a capacitated network denoting the transportation of shipments, at the arc level; (2) The service rescheduling at the arc level, mainly involving the service rescheduling and service usage. (3) The shipment flow re-planning and service rescheduling are connected through synchronization at the terminal, providing a dynamic solution within a day (Zhang and Pel, 2016; Corman et al., 2017b).

This model is expressed in terms of the decision variables with x_a^s and y_a^{dep}. x_a^s denotes the number of containers from shipment s routed to arc $a = (i, j, v)$; and $x_a^s \in \mathbb{N}^0 = \{0, 1, 2, ...\}$. y_a^{dep} denotes the rescheduled departure time via arc $a = (i, j, v)$.

4.1. Shipment flow conservation

Using the decision variable x_a^s, we regulate the consistence of the shipments from their origins to destinations throughout the network. Here we define $\delta_i^+ = \{(i, j, v) | j \in N, j \neq i, v \in V\}$ as the set of arcs starting from node i. Similarly, $\delta_i^- = \{(j, i, v) | j \in N, j \neq i, v \in V\}$ denotes the set of arcs arriving at node i.

Constraint (1) indicates that the difference value of incident volume and outgoing volume of shipment s at a certain node i should equal the required volume. To be more explicit, the required volume equals $-n^s$, n^s, and 0, at the shipment's origin terminal o^s, destination terminal d^s, and other transshipment nodes $i \in N \backslash \{o^s, d^s\}$.

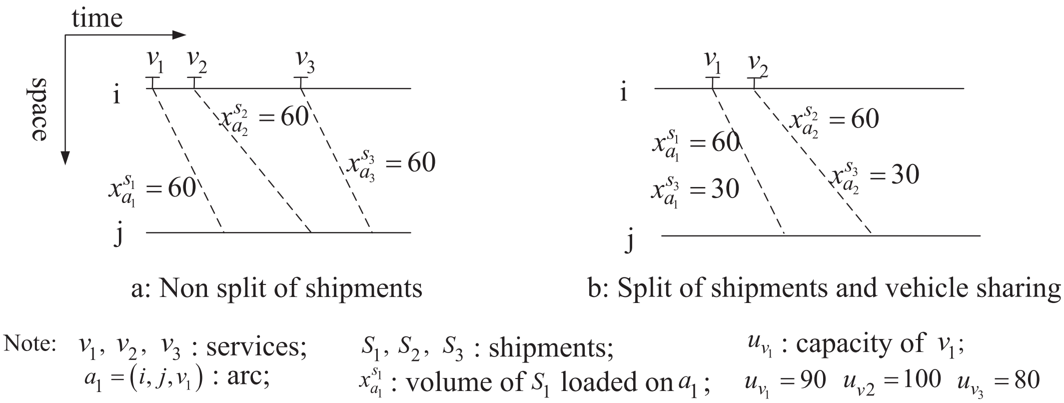

Fig. 3. A sample of shipment split and service sharing.

$$\sum_{a\in\delta_i^+} x_a^s - \sum_{a'\in\delta_i^-} x_{a'}^s = \begin{cases} -n^s, & \forall\, s\in S,\ \ if\ \ i = o^s \\ 0, & \forall\, s\in S,\ \ if\ \ i\in N\backslash\{o^s, d^s\}; \\ n^s, & \forall\, s\in S,\ \ if\ \ i = d^s \end{cases} \tag{1}$$

Constraint (1) makes it possible to split one shipment into more than one group of containers. It makes the most of the capacity of LCS. This shifts shipment flows to LCS and leads to a reduction in the transportation costs. Fig. 3 provides a simple example of the comparison of a *non-split* and a *split* of shipment. In the latter case, shipment s_3 is split among different services, using the remainder of those services' unused capacity.

Furthermore, constraint (2) makes sure the total load to arc $a = (i, j, v)$ from all shipments cannot exceed the capacity of the service v. To avoid any confusion, we want to make it clear again at this point that service v is pre-designed from node i to node j. Here the services' itineraries are consistent with the original SND plan.

$$\sum_{s\in S} x_a^s \leqslant u_v, \quad \forall\ a = \left(i, j, v\right) \in A; \tag{2}$$

To synchronize the shipment and service flows, the LSP needs to track the occupancy of arc a with the shipment of s. Thus an auxiliary binary variable b_a^s is introduced as an occupancy indicator. Meanwhile we adopt a sufficiently big number $\mathcal{M}$ to create the following constraints. In constraint (3), the $\mathcal{M}$ forces the $b_a^s = 1$ if the arc a is engaged by shipment s.

$$x_a^s \leqslant \mathcal{M}_{load}\cdot b_a^s, \quad \forall\ s\in S, \forall\ a = (i, j, v) \in A; \tag{3}$$

The LSP also has to monitor whether or not the pre-arranged service v is used or not in the re-planning. To that end, another auxiliary binary variables z_v is used for this purpose. Constraint (4) regulates $z_v = 1$ if the service v is used via any arc along its itinerary p_v.

$$\sum_{s\in S}\sum_{a\in p_v} x_a^s \leqslant \mathcal{M}_{load}\cdot z_v, \quad \forall\ v\in V; \tag{4}$$

4.2. Transshipment

This section extracts the transshipment at intermediate terminals as a result of the rerouting of the shipment flows. It is necessary to trace the transshipment regarding both the load and time dimension, since they generate costs and will further affect services rescheduling.

There are two kinds of transshipment: (1) transshipment involving the shipment flows. We model the transshipment with variable $n_{a,a',i}^s$, representing the number of containers belonging to shipment s from arc a to arc a' at a transshipment terminal $i\in N\backslash\{o^s, d^s\}$. At this point, we have to mention that there is no transshipment if the container uses the same service vehicle. (2) transshipment involving service vehicles. The binary variable $e_{a,a',i}$ is used to indicate whether services from arc a and arc a' need to be synchronized from the time dimension.

For the sake of simplicity, we define the arc before and after the transshipment as the feeder arc and the connecting arc respectively. Based on the pre-specified itinerary p_v, we record $F(v)$ and $L(v)$ as the first and last node of the itinerary. If node $i\in(p_v\backslash\{F(v), L(V)\})$, then the service v transverses node i via incident arc $\overleftarrow{(i, v)}$ and outgoing arc $\overrightarrow{(i, v)}$. For example, in Fig. 4, $\overleftarrow{(j, v_1)} = \left(i, j, v_1\right)$, $\overrightarrow{(j, v_1)} = \left(j, k, v_1\right)$, $L(v_2) = j$, $F(v_3) = j$. If the volume from shipment s should be unloaded from feeder arc a at node i, this volume is denoted by $\Delta_{a,i}^{s,-}$. Similarly, $\Delta_{a,i}^{s,+}$ refers to the volume from shipment s which will be loaded to connecting arc a.

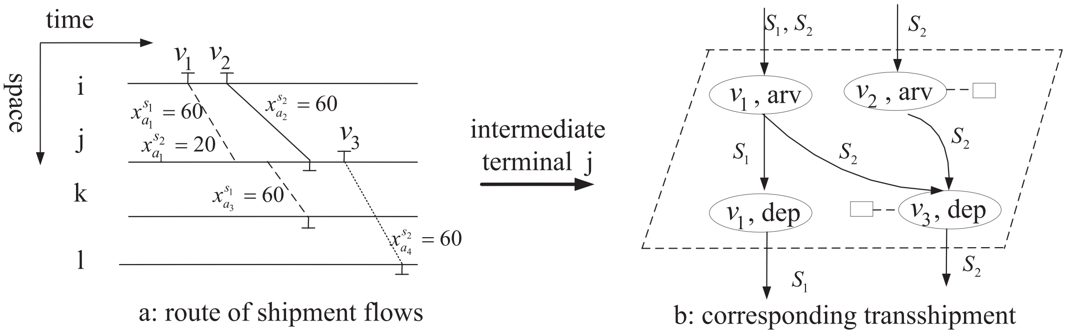

Fig. 4. A schematic illustration for transshipment.

The derivation procedure of tracking $n^s_{a,a',i}$ (the transshipped volume of shipment s) from $n^s_{a,a',i}$ (the re-routed shipment flow s) is described as following:

1) There exists a transshipment for shipment s at terminal i ($n^s_{a,a',i} > 0$) if and only if $\Delta^{s,-}_{a,i} > 0$ and $\Delta^{s,-}_{a,i} > 0$.
2) Constraints (5) and (6) describe the possible volume fluctuation (increase or reduction) of shipment s load on service v at node $i \in p_v$. The first line of Constraint (5) describe the situation in which the service v transverses i, meanwhile the second line describes when i is the last stop of service v.

$$\Delta^{s,-}_{a,i} \geqslant \begin{cases} (x^s_a - x^s_{a''}) & \text{if } L(v) \neq i, \text{ here } a'' = \overrightarrow{(i, v)}, \\ x^s_a & \text{if } L(v) = i, \end{cases} \forall\, s \in S, \forall\, i \in N \backslash \left\{o^s, d^s\right\}, \forall\, a = \left(i, j, v\right) \in \delta^-_i; \tag{5}$$

$$\Delta^{s,+}_{a',i} \geqslant \begin{cases} (x^s_{a'} - x^s_{a'''}), & \text{if } F(v') \neq i, \text{ here } a''' = \overleftarrow{(i, v')}, \\ x^s_{a'}, & \text{if } F(v') = i, \end{cases} \forall\, s \in S, \forall\, i \in N \backslash \left\{o^s, d^s\right\}, \forall\, a' = \left(i, j, v\right) \in \delta^+_i; \tag{6}$$

3) The value of $n^s_{a,a',i}$ can be determined as a minimum value between $\Delta^{s,-}_{a,i}$ and $\Delta^{s,+}_{a',i}$, which is presented as constraint (7). If $\Delta^{s,-}_{a,i} \geqslant \Delta^{s,+}_{a',i}$, then volume $\Delta^{s,-}_{a,i}$ are shifted to more than one services. Otherwise, the increased flow $\Delta^{s,+}_{a,a',i}$ are from more than one services.

$$n^s_{a,a',i} = \min(\Delta^{s,-}_{a,i}, \Delta^{s,+}_{a',i}), \qquad \forall\, s \in S, \forall\, a \in \delta^-_i, \forall\, a' \in \delta^+_i, \forall\, i \in N \backslash \{o^s, d^s\}, v' \neq v; \tag{7}$$

4) Finally, the binary variable $e_{a,a',i}$ takes on a value of 1 if there is a transshipment between arc a and arc a', which is presented in constraint (8).

$$\sum_{s \in S} n^s_{a,a',i} \leqslant \mathcal{M}_{load} \cdot e_{a,a',i}, \qquad \forall\, i \in N \backslash \left\{o^s, d^s\right\}, \forall\, a \in \delta^-_i, \forall\, a' \in \delta^+_i, v \neq v' \tag{8}$$

4.3. Service re-scheduling to synchronize shipment flows and service flows

Constraints (9a)–(13) discipline the rescheduling of services in the network. The actual departure time of service y^{dep}_a should be synchronized with the re-routed shipment flow x^s_a and the transshipment connection $e_{a',a,i}$. Meanwhile, the operating time of a barge or rail service should be based on the original timetable. Since it is impractical for these services to deviate too much from the pre-planned timetable. Note here the truck services are more flexible in the departure time.

The traverse time of an arc is k_a, making it possible to obtain the actual arrival time y^{dep}_a from the departure time y^{dep}_a. Parameters $h^{s,+}_{a,i}$ and $h^{s,-}_{a,i}$ are used to denotes the time needed to load or unload shipment s to or from an arc a at node i. Parameter $r_{a,a',i}$ stands for the duration for transshipment from arc a to a' at terminal i. Note in this work, we assume two or more loading activities can be executed pair-wisely. This also applies to the unloading and transshipment activities. We define ϕ^{dep}_a as a buffer time to regulate the maximum extra time it can be held. Fig. 5 illustrates the logic behind this buffer time.

Constraints (9a) and (9b) adjust y^{dep}_a, i.e., the actual departure time of a service. It is decided by the pre-designed departure time π^{dep}_a and the extra buffer time ϕ^{dep}_a. The evaluation of the buffer time depends on the service $a = (i, j, v)$. More precisely, it depends on the service mode m_v, the terminals i and j. (9a) reschedules barge and truck services, π^{dep}_a is the maximum length of holding time. For the rail services, we assume step-wise buffer time as shown in (9b). The actual departure time of a rail service is quite difficult to predict due to the complexity of railway operations. Thus we assume it is possible within every time unit ϕ^{dep}_a, for example 30 min or

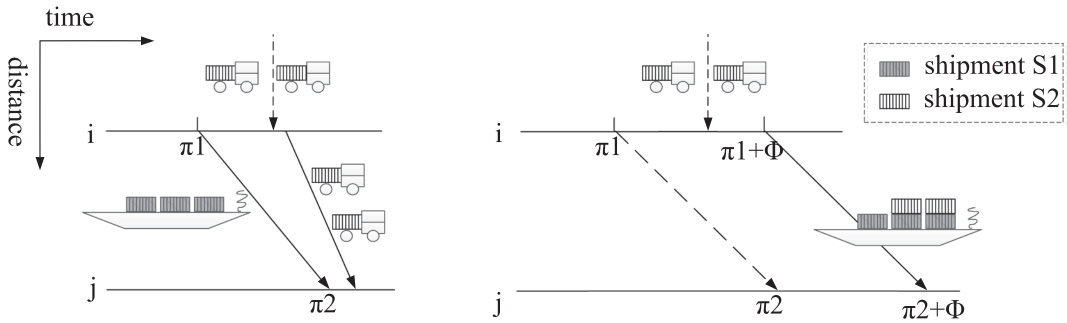

Fig. 5. Alignment of services departure time to synchronize the shipment flows.

60 min. The maximum holding time can be $k_{max}\cdot\phi_a^{\text{dep}}$.

$$y_a^{\text{dep}} \leqslant \pi_a^{\text{dep}} + \phi_a^{\text{dep}}, \quad \forall\ a = (i, j, v) \in \delta_i^+,\ m_v \in \{barge,\ truck\},\ \forall\ i \in N; \tag{9a}$$

$$y_a^{\text{dep}} = \pi_a^{\text{dep}} + k\cdot\phi_a^{\text{dep}}, \quad \forall\ a = (i, j, v) \in \delta_i^+,\ m_v = rail,\ k \in \{0, 1, 2. .k_{max}\},\ \forall\ i \in N; \tag{9b}$$

In addition, at the origin terminal of shipment s (i.e., o^s), the departure time of service a must be after the release time, which is regulated in constraint (10). Recall from constraint (3), $b_a^s = 1$ if flow from shipment s is rerouted to arc a.

$$y_a^{\text{dep}} + \mathcal{M}_{time}\cdot(1 - b_a^s) \geqslant \alpha^s + h_{a,i}^{s,+}, \quad \forall\ s \in S,\ \forall\ a = (i, j, v) \in \delta_i^+,\ i = o^s; \tag{10}$$

Constraint (11) derives the auxiliary decision variable y_a^{arv} from the running activity. The arrive time (at the end of the arc) equals the departure time (at the beginning of the arc) plus the transverse time in the case if $b_l = 1$, which means the service is used from constraint (4).

$$y_a^{\text{arv}} - y_a^{\text{dep}} + \mathcal{M}_{time}\cdot(1 - b_a) \geqslant k_a, \quad \forall\ a = (i, j, v) \in A; \tag{11}$$

Finally, constraints (12) and (13) regulate how long services dwells at terminal i. The departure time should be later than its anterior arrival time, plus transshipment time, if that exists.

$$y_{a'}^{\text{dep}} - y_a^{\text{arv}} \geqslant \mathcal{M}_{time}\cdot(1 - z_v), \quad \forall\ i \in N,\ \forall\ a' = (j, i, v) \in \delta_i^+,\ \forall\ a = (i, j', v) \in \delta_i^-; \tag{12}$$

$$y_{a'}^{\text{dep}} - y_a^{\text{arv}} \geqslant h_{a,i}^{s,-} + r_{a,a',i} + h_{a,i}^{s,+} - \mathcal{M}_{time}\cdot(1 - e_{a,a',i}),\ \forall\ i \in N,\ \forall\ a' = (j, i, v) \in \delta_i^+,\ \forall\ a = (i, j', v) \in \delta_i^-; \tag{13}$$

4.4. Shipment due time constraints

Constraints (14a)–(17) are used to make sure that all the shipments arrive within the expected time window. Shipment s can arrive ahead of or after the expected due time γ^s. Since the splitting of shipment is built into constraint (1), one shipment s can arrive at the destination $j = d^s$ in the shape of embranchments via any possible arc $a = \delta_i^+$. From (3), we can obtain the distribution of the shipment flows to all these possible arcs. If $b_a^s = 1$ ((part of) the shipment is assigned to the arc a) the arrive time equals the arrive time of the arc y_a^{arv} plus the unloading time. On the other hand, if $b_a^s = 0$, then delivery time is not related to the arrival event.

Taking into account the aforementioned description, variable t_a^s is used to represent the final delivery time of containers from shipment s delivered via $a \in \delta_j^+$ at the destination terminal $j = d^s$, which is determined by constraints (14a) and (14b).

$$t_a^s \geqslant y_a^{\text{arv}} + h_{a,i}^{s,-} - \mathcal{M}_{time}\cdot(1 - b_a^s), \quad \forall\ s \in S,\ \forall\ a = (i, j, v) \in \delta_j^-, j = d^s; \tag{14a}$$

$$t_a^s \leqslant y_a^{\text{arv}} + h_{a,i}^{s,-} + \mathcal{M}_{time}\cdot(1 - b_a^s), \quad \forall\ s \in S,\ \forall\ a = (i, j, v) \in \delta_j^-, j = d^s; \tag{14b}$$

Constraint (15) makes sure that the delivery time of each split shipment t_a^s should be before γ^s, which is the latest delivery time.

$$t_a^s \leqslant \gamma^s, \quad \forall\ s \in S,\ \forall\ a = (i, j, v) \in \delta_j^+, j = d^s; \tag{15}$$

We use $[w_a^{s,-}, w_a^{s,+}]$ to denote the corresponding earliness or latency. Constraints (16) and (17) exacts the deviation of t_a^s (the shipment arrival time) from β^s (the expected due time). Note that for shipment t_a^S only one of earliness or delay can occur.

$$w_a^{s,-} \geqslant (\beta^s - t_a^s) - \mathcal{M}_{time}\cdot(1 - b_a^s), \quad \forall\ s \in S,\ \forall\ a = (i, j, v) \in \delta_j^-, j = d^s, \tag{16}$$

$$w_a^{s,+} \geqslant (t_a^s - \beta^s) - \mathcal{M}_{time}\cdot(1 - b_a^s), \quad \forall\ s \in S,\ \forall\ a = (i, j, v) \in \delta_j^-, j = d^s. \tag{17}$$

4.5. Objective function

The optimization model is formulated as a mixed-integer programming problem (MIP). The objective is to minimize the total operating cost based on on-time delivery expectations.

We briefly introduce related parameters for the operating costs. f_v is the fixed cost of using the service v, ψ_v is the cancellation fee if the pr-planned LCS are not used, c_a is the variable cost of routing a unit of shipment on arc a. In addition we define g_i^s as the unit transshipment cost for shipment s at terminal i. The early arrival penalty $\rho^{s,-}$ is generated from storage cost at the destination, and the late penalty $\rho^{s,+}$ is made from the contract with the shipper, depending on the value and urgency of the goods.

The total operating costs are expressed as C in (18), which includes: the fixed costs of used services C^{f}, the flow transportation costs C^{c}, the transshipment costs C^{t}, and the penalty costs due to early delivery C^{e} or late delivery C^{l} at the destinations. The fixed costs in (19) include the total fixed costs of the service being used from all transportation modes, and the cancellation fees for the pre-specified services. Constraint (20) describes the total variable transportation costs, which increase linearly with the transported volume x_a^s. The transshipment costs are calculated by constraint (21). The penalty of off-target time delivery at the destination $i = d^s$ consists of early arrival penalty (22) and late arrival penalty (23). The early and late arrival penalty synchronize the shipments, which occurs when several shipments are waiting to be transported at the same terminal while service capacity is insufficient. Thus, the loading or the holding of the shipments is balanced according to the delivery time.

$$\text{Min } C^{\mathrm{f}} + C^{\mathrm{c}} + C^{\mathrm{t}} + C^{\mathrm{e}} + C^{\mathrm{l}}, \tag{18}$$

where,

$$C^{\mathrm{f}} = \sum_{v\in V} (z_v\cdot f_v) + \sum_{v\in V} (1 - z_v)\cdot\psi_v, \tag{19}$$

$$C^{\mathrm{c}} = \sum_{s\in S}\sum_{a\in A} (x_a^s\cdot c_a), \tag{20}$$

$$C^{\mathrm{t}} = \sum_{s\in S}\sum_{i\in N\setminus\{o^s,d^s\}}\sum_{a,a'\in A} (n_{a,a',i}^s\cdot g_{a,a',i}^s), \tag{21}$$

$$C^{\mathrm{e}} = \sum_{s\in S}\sum_{a\in\delta_j^-,j=d^s} (x_a^s\cdot\rho^{s,-}\cdot w_a^{s,-}), \tag{22}$$

$$C^{\mathrm{l}} = \sum_{s\in S}\sum_{a\in\delta_j^-,j=d^s} (x_a^s\cdot\rho^{s,+}\cdot w_a^{s,+}). \tag{23}$$

4.6. Linearization of objective function

The mathematical model is formulated in linear constraints (1)–(17), with a non-linear term objective function (22) and (23). To linearize the objective function, we assume that storage costs or delay penalty are charged per TEU and per time interval (for example per 10 min interval). This assumption is consistent with current practice in synchromodal transportation.

Take (22) as demonstration, the maximum possible value of auxiliary variable $w_a^{s,-}$ can be estimated in advance. It can be calculated as the due time minus the earliest arrival time of all services at the destination terminal. Let $\dot{\pi}^{s,arv}$ denote the earliest possible arrival time, $\dot{\pi}^{s,arv} := min(\pi_a^{arv})$, where $\forall\ a \in \delta_j, j = d^s$). The maximum earliness duration can be equally divided into $\mathcal{K}$ time slots, each of which equals $(\beta^s - \dot{\pi}^{s,arv})/\mathcal{K}$, where β^s is the due time of shipment s. Another auxiliary variable $\theta_a^{s,\mathfrak{k}}$ will be used, if $\theta_a^{s,\mathfrak{k}} = 1$, denoting the earliness $w_a^{s,-}$ eventually is true in the $\mathfrak{k}$ -th time slot, otherwise $\theta_a^{s,\mathfrak{k}} = 0$. Thus constraint (22) can be expressed as following:

$$C^{\mathrm{e}} = \sum_{s\in S}\sum_{a\in\delta_j,j=d^s}\sum_{\mathfrak{k}=1}^{\mathcal{K}} (x_a^s\cdot(\rho^{s,-}/\mathcal{K})\cdot\theta_a^{s,\mathfrak{k}}) \tag{24}$$

$$r_a^s + \mathcal{M}_{time}\cdot(1 - \theta_a^{s,\mathfrak{k}}) \geqslant (\beta^s - \dot{\pi}^{s,arv})/\mathcal{K}, \qquad \forall\ s \in S, \forall\ a = (i, j, v) \in \delta_j, j = d^s, \forall\ \mathfrak{k}\in 1..\mathcal{K} \tag{25}$$

The same process is applied to deal with (23), resulting in (26) and (27):

$$C^{\mathrm{l}} = \sum_{s\in S}\sum_{a\in\delta_j,j=d^s}\sum_{\eta=1} \mathcal{H}(x_a^s\cdot(\rho^{s,+}/\mathcal{H})\cdot\lambda_a^{s,\eta}) \tag{26}$$

$$w_a^s + \mathcal{M}_{time}\cdot(1 - \lambda_a^{s,\eta}) \geqslant (\gamma^s - \beta^s)/\mathcal{H}\cdot\eta, \qquad \forall\ s \in S, \forall\ a = (i, j, v) \in \delta_j, j = d^s, \forall\ \eta \in 1..\mathcal{H} \tag{27}$$

As such, the model is reformulated with objective (18) (deposed into (19)–(21), (24)–(27)), and is constrained by (1)–(16). The model will be referred to as the STP (synchromodality transportation planning) model for short.

5. Re-planning algorithm

The general steps of the replanning procedure are included in Algorithm 1:

Algorithm 1. Re-planning Algorithm

Input: Set of unexpected events, current status of the network.
Output: Re-planning solution, the integrated shipment flow rerouting, transshipment and service rescheduling.
procedureProcedure re-plan when (an) unexpected event(s) occur(s)
    Step 1: Initialize the network.
    Step 2: Apply the pre-processing:
    Step 3: Solve the STP model.

5.1. Initialize the network

The initialization includes inputting the information of the terminals, services, arcs and shipments. The status of the network should also be recorded, including the on-going transportation operations. The STP model can be used to re-plan the operations directly after an unforeseen situation occurs, which may include any fluctuations or deviation from the original plan.

5.2. Applying the pre-processing

In the following section, we describe the pre-processing steps designed to improve the computational performance of the algorithm. The pre-processing including (1) tightening the re-planning time window, (2) fixing (part of) variables, and (3) reducing of the number of transshipment variables.

Tightening the re-planning time window

The replanning starts immediately after the unexpected event occurs, which is denoted as $\mathcal{T}^{start}$. The replanning ends at $\mathcal{T}^{end} = max\{\gamma^s| \quad \forall s \in S\}$. Thus the replanning window is set as $[\mathcal{T}^{start}, \mathcal{T}^{end}]$.

Fixing part of variables

All the decisions those have been made before the unexpected event occurs are not affected. This means that any variables corresponding to those decisions are fixed. Meanwhile, the arcs in which the services are broken down will be eliminated from the network.

Reducing of the number of transshipment variables

The number of transshipment variables is the largest number among all the variables, because of the uncertainties in three dimensions: the feeder arcs, the connecting arcs, and the rerouting of shipment flow. Consider the possible transshipment connection from arc $a \in \delta_i^-$ to arc $a' \in \delta_i^+$. We can extract from this arc the earliest possible arrival time $\tilde{t}_a^{arv}$ and the latest possible departure time $\tilde{t}_{a'}^{dep}$. Then $n_{a,a',i}^s = 0$, $e_{a,a',i} = 0$ in the case of $\tilde{t}_a^{arv} \geqslant \tilde{t}_{a'}^{dep}$. Thus, the problem-solving efficiency can be improved significantly if the number of the transshipment variables can be reduced.

5.3. Solving the STP model

After initializing and pre-processing, the STP model can be solved using the CPLEX solver. A minimum cost replanning proposal will be generated, which is an integrated shipment flow replanning, terminal transshipment, and the service rescheduling. Here need to consider the value of big-$\mathcal{M}$ to be given to the solver.

Customized value of $\mathcal{M}$

The big-$\mathcal{M}$ is used in the constraints. The evaluation of $\mathcal{M}$ can be divided into two categories according to the applied situation. $\mathcal{M}_{load}$ is used in (3), (4), (8). We evaluate $\mathcal{M}_{load} := max\{u_v)| \ \forall v \in V\}$. The second category $\mathcal{M}_{time}$ is used in (10)–(14b), (16), (17), (25) and (27) to regulate the services operation time. We evaluate $\mathcal{M}_{\text{time}} := \mathcal{T}^{\text{end}}$.

6. Computational experiments

In this section, we demonstrate the applicability of the model in a real-word transportation case. The optimization model is coded and solved in CPLEX 12.8.0 on a computer with an Intel Core i5-4690 3.2 GHz processor and 8 GB of RAM. All the instances are solved within the time limit within seconds.

The computational experiments are performed in two parts. Firstly, we present a description of the Rotterdam hinterland network and its daily transportation tasks. A base case is provided as an original plan. Secondly, we test the STP model on different initial perturbations. These include includes exogenous perturbations from shipments(late release and volume fluctuations), endogenous disturbances from services (delays), and some mixed events. The computational experiments show that the STP model has the flexibility to deal with perturbations via the rerouting of shipment flows and the service rescheduling.

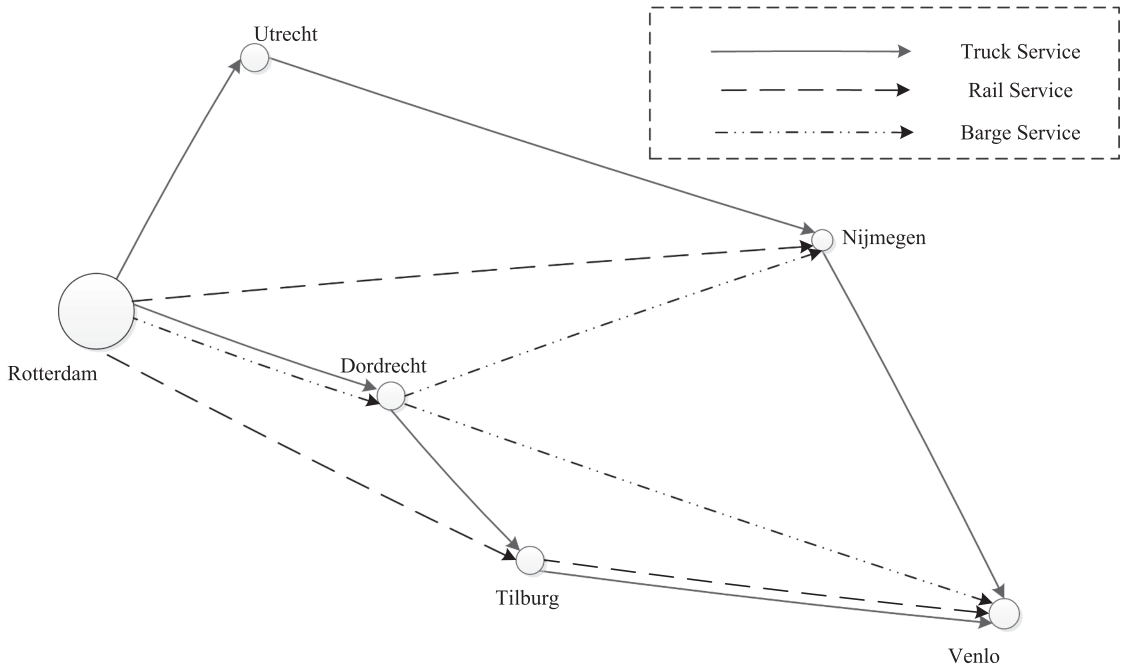

Fig. 6. The Rotterdam hinterland transportation network.

6.1. Network description

To test the STP model, we construct our case based on the network presented by Guo et al. (2018), as shown in Fig. 6. There are six terminals in the studied network, i.e., Port of Rotterdam (PoR in short), Utrecht, Nijmegen, Dordrecht, Tilburg and Venlo. All shipments are transported from PoR to the other five terminals. In this network, three different transportation modes (i.e., barge, rail and truck services) are used in combination. For instance, the two arcs from PoR to Dordrecht represent a barge service and truck services.

A summary of the parameters used in our case study is presented in Table 2. The fixed costs (€/ service) of the service are based on the typical monetary costs of services per mode. The transportation time is calculated as the sum of the loading time, the net travelling time and the unloading time. Besides, we set the loading and unloading time of LCS and truck services to one hour and a half hours respectively. We consider one hour for transshipment time (Li et al., 2017). Transshipment cost is set as 23.89 (€/TEU) (Li et al., 2017). Note that we also allow transshipment between services of the same mode (e.g. transshipment from one barge service to another is possible).

During the re-planning, we assume the cancellation of LCS will generate half of the fixed cost, i.e., $\psi_l := 0.5{\cdot}f_v$ in constraint (19). The values of the buffer time in constraints (9a) and (9b) are set to $\phi_a^{dep} := 3$(hours) and $k_{max}{\cdot}\phi_a^{dep} := 1$(hour). The customized evaluations of ϕ_a^{dep} should be decided by the local LSP according to the specific situations, which is briefly discussed in Section 7.1.

Table 2
Data set of the services in the Rotterdam hinterland.

Arc (Dep S, Arv S, Service)	Mode	Capacity (TEU)	Travel Time (hour)	Fixed Cost (€/service)	Variable Cost* (€/TEU)
PoR, Dordrecht, v0001	Barge	120	2	60	2.45
PoR, Tilburg, v0002	Rail	100	2	30	30.16
PoR, Nijmegen, v0003	Rail	60	2	30	30.16
Dordrecht, Nijmegen,v0004	Barge	120	5	60	4.29
Dordrecht, Venlo, v0005	Barge	120	9	60	6.73
Tilburg, Venlo, v0006	Rail	100	1	30	22.16
PoR, Utrecht, v0007-v0506	Truck	1	1	15	61.96
PoR, Dordrecht, v0507-v1006	Truck	1	0.5	15	30.98
Utrecht, Nijmegen,v1007-v1506	Truck	1	1	15	61.96
Dordrecht, Tilburg,v1507-v2006	Truck	1	1	15	30.98
Tilburg, Venlo, v2007-v2506	Truck	1	1	15	30.98
Nijmegen, Venlo, v2507-v3006	Truck	1	1	15	30.98

Variable Cost ∗ is from Guo et al. (2018).

Table 3
Transportation shipments from port of Rotterdam to 5 hinterland terminals.

s	o^s	d^s	n^s (TEU)	α^s (h)	β^s (h)	γ^s (h)	$\rho^{s,-}$ (€/TEU/h)	$\rho^{s,+}$ (€/TEU/h)
S1	PoR	Utrecht	50	7	18	24	0.5	1.5
S2	PoR	Dordrecht	50	7	18	24	0.5	1.5
S3	PoR	Tilburg	50	7	18	24	0.5	1.5
S4	PoR	Nijmegen	100	7	18	24	0.5	1.5
S5	PoR	Venlo	100	7	18	24	0.5	1.5

6.2. Base case

We put five shipments into the network, as described in Table 3. Each shipment s is characterized by its origin terminal (o^s), destination terminal (d^s), container volume n^s, release time (α^s), due time (β^s), latest delivery time (γ^s), and penalties for early ($\rho^{s,-}$) or late delivery ($\rho^{s,+}$).

Table 4 shows the pre-planned solution if there are no disturbances. We use this solution as a base to verify how the STP model deals with the disturbances.

For the base case, the total cost C (€) is 15961, in which $C^f = 1320$, $C^c = 10476$, $C^t = 3345$, $C^e = 205$, and $C^l = 615$. These costs are described in the objective function (18)–(23). For the solution, 10.42% of the shipment is transported by truck services. While, the shares of rail and barge services are 38.64% and 50.94%, respectively. The modal split is calculated as the ratio of a freight mileage (TEU × km) of a certain mode against the overall used freight mileage. Meanwhile, the utilization rates of barge and rail services are 49.27% and 85.67%. Note that the utilization rate (%) is calculated as the ratio of (i) the used freight mileage (TEU × km) and (ii) the product of the full capacity of the service and the pre-planned running distance.

6.3. Key performance indicators (KPI)

We use 11 Key Performance Indicators (KPIs) to test the performance of the STP model. The KPIs are categorized into three groups indicating (1) the flexibility of the solution, (2) the LSP performance or (3) the service level. There are two KPIs in the first group: the amount of the re-routed shipment flows (TEU) and the rescheduled time of all LCS (vehicles × delayed hours). The second group of KPIs includes the variation rate of fixed service cost $\pm C^f$ (where $\pm$ denotes the variation of the costs), the variation rate of variable cost $\pm C^c$, the variation rate of transshipment cost $\pm C^t$, the variation of the modal split rate (%) of LCS, the variation of utilization rate (%) of LCS, the number of cancelled LCS, and the number of additional truck services. The final group consists of the early delivery (TEU × h) and late delivery (TEU × h) at the destinations.

6.4. Delays, STP solutions and corresponding KPIs

In this section, we discuss the results of the STP replanning in the cases where occur the delay of shipment release or LCS. The results are listed in Tables 5 and 6, respectively. In these tables, the first two columns represent the incident case and the third column demonstrates the associated delay. For instance, the first row indicates the replanning solutions if shipment $s2$ encounters a delay of 0.5 h.

The STP model tailors different replanning solutions according to the duration of the delay. If shipments are slightly delayed, no adjustments are needed. That is because of the time gap between the departure services and the expected release time of the shipments. However, when there are longer delays, the STP model initially resorts to service rescheduling. The LCS vehicles are held longer than the original timetable to process the intake of the delayed shipments. When the delays get even longer, the STP model combines the rerouting of shipments and the service rescheduling.

Table 4
The base case: the original shipment assignment and service schedules.

Arc	Mode	S1	S2	S3	S4	S5	Start Time	End Time
PoR, Dordrecht, v0001	Barge		30		40	50	7	11
PoR, Tilburg, v0002	Rail			50		50	10	14
PoR, Nijmegen, v0003	Rail				60		14	18
Dordrecht, Nijmegen, v0004	Barge				40		15	22
Dordrecht, Venlo, v0005	Barge					50	12	23
Tilburg,Venlo, v0006	Rail					50	15	18
PoR, Utrecht,v0007-v0506	Truck	50					16	18
PoR, Dordrecht,v0507-v0526	Truck		20				16.5	18

Note: S1-S5: Shipment 1-Shipment 5. DepS/ArvS: Departure/Arrival Station.
Start T: time to start loading, the service departures afterwards, which takes $h^s_{a,i}$.
End T: time when unloading finished, the service arrives before, with interval $h^s_{a,i}$.

Table 5
Late release of shipments and corresponding KPIs of the STP solutions.

	Delays	Severity	Shipment re-routing (TEU)	LCS Rescheduling (vehicle × h)	$\pm C^f$ (%)	$\pm C^c$ (%)	$\pm C^t$ (%)	Cancelled LCS	Extra Trucks	± LCS modal split (%)	± LCS utilization (%)	± Early Delivery (TEU × h)	± Delayed delivery (TEU × h)
Shipment	**S2**	0.5h	0	0	0	0	0	0	0	0	0	0	0
		1h	0	1	0	0	0	0	0	0	0	-10	50
		1.5h	60	0	34.09	-4.31	0	0	30	-2.1	-4.7	-210	150
	S3	$\leq$ 3h	0	0	0	0	0	0	0	0	0	0	0
		3.5h	0	1	0	0	0	0	0	0	0	-25	25
		4.0h	0	2	0	0	0	0	0	0	0	-50	50
	S4	0.5h	0	1	0	0	0	0	0	0	0	-15	25
		1h	0	2	0	0	0	0	80	-11.48	-8.2	-30	50
		1.5h	80	0	22.73	-2.88	0	0	20	0	0	140	100
	S5	0.5h	0	1	0	0	0	0	0	0	0	-15	25
		1h	0	2	0	0	0	0	0	0	0	-30	50
		1.5h	80	1.5	34.09	8.17	0	0	30	-4.8	-2.5	-10	0

Table 6
Latency of the LCS and corresponding KPIs of the STP solutions.

	Delays	Severity	Shipment re-routing (TEU)	LCS Rescheduling (vehicle × h)	$\pm C^f$ (%)	$\pm C^c$ (%)	$\pm C^t$ (%)	Cancelled LCS	Extra Trucks	± LCS modal split (%)	± LCS utilization (%)	± Early Delivery (TEU × h)	± Delayed delivery (TEU × h)
Services	**v0001**	0.5h	0	0	0	0	0.5	0	0	0	0	-15	25
		1h	0	1	0	0	0	0	0	0	0	-30	50
		1.5h	60	2	34.09	8.17	0	0	30	-4.8	-2.5	-10	0
	v0002	0.5h	70	0.5	0	0	0	0	0	0	0	-25	25
		1h	0	1	0	0	0	0	0	0	0	-50	50
		1.5h	100	1	55.68	-7.19	0	1	50	-7.7	-3.4	-335	250
	v0003	0.5h	0	0	0	0	0	0	0	0	0	0	30
		1h	0	0	0	0	0	0	0	0	0	0	60
		1.5h	0	0	0	-2.88	0	0	20	0	0	140	100
	v0004	0.5h	0	0	0	0	0	0	0	0	0	0	90
		1h	0	0	0	0	0	0	0	0	0	0	40
		1.5h	0	0	0	0	0	0	0	0	0	0	60
	v0005	0.5h	0	0.5	0	0	0	0	0	0	0	-15	25
		1h	0	1	0	0	0	0	0	0	0	-30	50
		1.5h	80	3	154.55	113.62	135.70	1	50	-7.3	-5.1	320	560
	v0006	0.5h	0	0.5	0	0	0	0	0	0	0	-25	25
		1h	0	1	0	0	0	0	0	0	0	-50	50
		1.5h	0	1	0	0	0	0	0	0	0	-50	75

Table 7
Volume Fluctuations and corresponding KPIs.

	Shipment	Severity	Flow Re-routing (TEU)	LCS Re-scheduling (vehicle ×h)	$\pm C^f$ (%)	$\pm C^c$ (%)	$\pm C^t$ (%)	Cancelled LCS	Extra Trucks	± LCS modal split (%)	± LCS utilization (%)	± Early Delivery (TEU × h)	± Delayed delivery (TEU × h)
Volume increase	**S2**	+10%	0	0	5.68	1.48	0	0	5	-0.7	0	0	0
		+20%	0	0	11.36	2.96	0	0	10	-1.4	0	0	0
		+30%	0	0	17.05	4.44	0	0	15	-2.1	0	0	0
	S3	+10%	10	0	5.68	0.72	0	0	5	-0.6	-0.6	-42.5	47.5
		+20%	20	0	11.36	1.44	0	0	10	-1.2	-1.2	-30	50
		+30%	30	0	17.05	2.16	0	0	15	-1.8	-1.8	45	75
	S4	+10%	20	0	11.36	3.37	7.14	0	10	-1.2	1.4	-70	40
		+20%	40	0	22.73	6.73	14.28	0	20	-2.3	2.8	-140	80
		+30%	60	0	34.09	10.10	21.43	0	30	-3.3	4.3	-210	120
	S5	+10%	20	0	11.36	3.60	7.14	0	10	-1.0	2.4	-70	50
		+20%	40	1	22.73	7.20	14.28	0	20	-2.0	4.9	-165	125
		+30%	60	0	24.09	10.80	21.43	0	30	-2.8	7.4	-210	150
Volume decrease	**S2**	-10%	0	0	-5.68	-1.48	0	0	-5	0.7	0	0	0
		-20%	0	0	-11.36	-2.96	0	0	-10	1.5	0	0	0
		-30%	0	0	-17.05	-4.44	0	0	-15	2.3	0	0	0
	S3	-10%	10	0	-5.68	-0.72	0	0	-5	0.6	-0.6	15	-25
		-20%	20	0	-11.36	-1.44	0	0	-10	1.3	-1.2	30	-50
		-30%	30	0	-17.05	-2.16	0	0	-15	2.0	-1.9	45	-75
	S4	-10%	10	0	-11.36	-3.37	-7.14	0	-10	1.3	-1.4	70	-40
		-20%	20	0	-22.73	-6.73	-14.28	0	-20	2.7	-2.9	140	-80
		-30%	30	0	-22.73	-11.54	-21.43	0	-20	2.4	-5	140	-70
	S5	-10%	10	0	-11.36	-3.60	-7.14	0	-10	1.1	-2.5	70	-50
		-20%	20	1	-22.73	-7.20	-14. 28	0	-20	2.4	-4.9	115	-75
		-30%	20	0	-22.73	-12.24	-21.43	0	-20	2.0	-8.1	140	-100

The STP model can also manage service delays, as shown in Table 6. Rerouting of shipment flows is used as the primal solution. In addition, the rescheduling of other LCS is also used to solve severe delays.

Sometimes the delay propagates from one service to another one from the transshipment connection. It needs to be pointed out that there are two cases in which a barge or a rail service is cancelled. In the first case where rail service $v0002$ is delayed for 1.5 h, while the STP does not assign any shipment flows to rail service $v0006$. This is because of the buffer time $\phi_a^{\text{dep}} := 1$ hour for the arc *Dordrecht*, *Venlo*, $v0006$ in constraint (9b), which precludes transshipment from service $v0002$ to service $v0006$.

6.5. Shipment fluctuations, STP solutions and corresponding KPIs

In this section, we test the STP model with volume fluctuations of shipments. Table 7 presents the input fluctuations and corresponding KPIs. The first column illustrates to from which shipment the volume fluctuation rises from, and the second column indicates the severity of the fluctuation.

The solutions mainly use the re-routing of the shipment flows. That is because the perturbations are caused by volume fluctuations. In the rerouting module, the increased volume is mostly handled by the LCS. This is the result of the lower fixed cost f_v and variable cost c_l of LCS compare to those of truck services. Meanwhile, the re-scheduling of LCS is updated when necessary to extend the possibility of taking in more flows. However, additional truck services are still used when there is no available capacity from the LCS.

When the volume of shipments decreases, the STP model primarily cancels the usage of trucks. This also leads to a higher modal split of LCS in these particular cases.

Table 8
Mixed events, solutions and the corresponding KPIs.

Perturbation 1	Perturbation 2	Flow Re-routing (TEU)	LCS Re-scheduling (vehicle ×h)	$\pm C^f$ (%)	$\pm C^c$ (%)	$\pm C^t$ (%)	Cancelled LCS	Extra Trucks	± LCS modal split (%)	± LCS utilization (%)	± Early Delivery (TEU × h)	± Delayed delivery (TEU × h)
S2+2h	**S3+2h**	60	0	34.09	-4.32	0	0	30	-4.7	-2.1	210	150
S2+2h	**S5+2h**	70	3	34.09	8.17	0	0	30	-4.8	-2.5	-10	0
S3+2h	**S4+2h**	150	3	54.54	13.62	35.71	1	50	-7.4	-5.2	-90	150
S4+2h	**S5+2h**	70	3	34.09	8.17	0	0	30	-4.8	-2.5	-10	0
v0001+1h	**v0002+1h**	0	2	0	0	0	0	0	0	0	-80	100
v0001+1h	**v0004+1h**	100	1	22.73	-2.88	0	0	20	-3.14	-1.37	90	210
v0001+1h	**v0005+1h**	70	2	34.09	8.17	0	0	30	-4.76	-2.47	-10	50
v0002+1h	**v0006+1h**	70	3	34.09	8.17	0	0	30	-4.76	-2.47	-60	50

6.6. Mixed events, STP solutions, and corresponding KPIs

To further examine the solution strategy and its performance in greater detail, we introduce simultaneous events to the network and the STP model.

To summarize, we obtain the following attributes of the STP models from the cases in Table 5 - Table 8. The STP model tailors different re-planning solutions to the specific encountered disturbance each time. Adjustments in the time dimension (service re-scheduling) are made to deal with the delays; adjustments in the space dimension (rerouting of shipment flows) are made to deal with volume fluctuations. If the disturbances are comparatively severe, the STP resorts to a combination of the rescheduling and rerouting.

The operating costs increase when dealing with the late release of shipments, service delays and increased shipment volume. The costs can increase sharply in the case of cancelling a LCS. The cancellation is due to the delay propagate from one service to another. The resulting delay substantially violates the planned operating time. Finally, some shipments are delivered later than the expected due time, which is unavoidable in managing the disturbances.

7. Computational analysis

Based on the computational experiments, we also analyze it looking at three other aspects. Firstly, we check the critical path of the example network to see if it is possible to improve the service rescheduling flexibility any further. Secondly, the proposed model is compared to other rigid re-planning methods to access the value of shipment split and flexible service scheduling. Finally, the model is tested based on more theoretical instances to explore the difficulty of the model resolution.

7.1. Critical path and the re-scheduling flexibility

Refinements can be made to tailor the value of ϕ_a^{dep} in constraint (9a). This parameter regulates the limit of extra waiting time before a departure event. If ϕ_a^{dep} can be individually tailored, the rescheduling flexibility of model can be reinforced. To illustrate this more clearly, we take the delivery of shipment $S5$ as an example.

We visualize the paths of $S5$ in which only barge or rail services are used (see Fig. 7). It is constructed based on the critical path

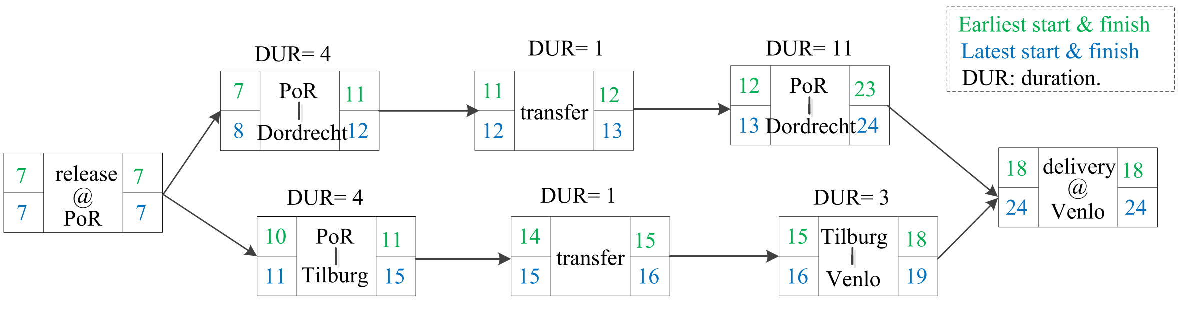

Fig. 7. The Critical Path for shipment 5 to use Large Capacity Services.

method. The upper route *PoR*, *Dordrecht*, *v*0001 - *Dordrecht*, *Venlo*, *v*0005 (route 1 in short) has an elasticity of one hour. Here, it is determined by the maximum due time (γ^{S5}). On the other hand, the lower route *PoR*, *Tilburg*, *v*0002 - *Tilburg*, *Venlo*, *v*0006 (route 2 in short) also has one hour elasticity. Here it is determined by ϕ_a^{dep} for the arc a = *PoR*, *Venlo*, *v*0006, which limits the possibility of additional waiting and transshipment. Whereas as shown in Table 6 the connecting train *v*0006 is cancelled when service *v*0002 is 1.5 h delayed.

The are three reasons for extending this buffer time. (1) The constraint of the latest finish time (γ^{S5}) can still be satisfied; (2) We assume rail service *v*0006 or the locomotive has no other immediate tasks. (3) The resulting transshipment costs and delay penalty can be compensated by switching from trucks into rail services.

The rescheduling of railways in the multi-modal transportation

The rescheduling of the rail services in practice is quite complex in the real application. The railway is an important component of the multi-modal network. However, most intermodal or synchromodal literature avoid talking about the exact operation time of rail services. For example, Pérez and Mes (2017) model it as a day to day service in synchromodal transportation. This kind of assumption makes the work cannot be used for flexible replanning in real-time.

One of the few studies to deal with exact freight trains departure time in the multi-modal freight network was Corman et al. (2017b). Another study include the terminal freight train operation was Hu et al. (2018). Both studies regulate the departure time by using a pre-planned time plus a buffer time. Here we use the same logic as Corman et al. (2017b) and Hu et al. (2018). We additionally refined it as a step-wise buffer time according to constraint (9b).

The departure times of rail services are more limited for safety reasons. If the freight rail services run on dedicated rail tracks (like the Betuweroute line from Rotterdam to Germany), the departure times should meet a headway separation constraint. If the rail cargoes share the same railway track with passenger trains, usually priority is given to passenger trains, Corman et al. (2011). Generally speaking, the rescheduling solution of railways is expected in minutes Crainic et al. (2014).

With the developed information & communication and technology (ICT) and the synchromodal platform, the railway operators can keep up with the expected flexibility. Secondly if the rail service is held within a buffer time, it will take accumulated shipment *en route*; otherwise the train will be cancelled and the shipment flow goes to truck services. From the optimization aspects, this study illustrates what the railway company can do (re-scheduling) in the multimodal transportation, and how the railway company can benefit (more shipment flows and improved modal split).

7.2. The value of shipment split and flexible scheduling

In this section, we compare the solution obtained by the STP model against two reference models. In the first case, we consider a case splitting of the shipment is not conducted (N-STP). For the second case, we consider a case where the network has a rigid schedule (R-STP).

To keep the comparison detailed and at the same time keep this section concise, we use one particular case in which LSP is informed in advance that the release time shipments *S*4 and *S*5 will be delayed by two hours. In other words, $\alpha^{S4} = 7 \rightarrow 9$, $\alpha^{S5} = 7 \rightarrow 9$. The reference N-STP model and R-STP model will be discussed in the following subsections. Table 9 summaries the KPIs obtained by solving the three models. For the detailed solutions, see Table A.12, A.13, A.14 in Appendix A.

The STP resolutions save 16.11% and 10.52% of the operational costs than the N-STP resolutions and the R-STP resolutions. These saving costs can be tracked to the fixed and variable costs of the services, since the STP model uses fewer truck services. Meanwhile, the STP resolutions are less punctual compared to two reference models, which means that there are some additional early and late delivery penalties. That is due to the less usage of truck services. Furthermore, the results indicate that by splitting the shipment, the LSP can increase the share of barge and rail services. Moreover, the utilization rates of the available barge and rail services from the solution of the STP model are higher than those of the two reference models. It is due to time & space-related flexibility that the STP model shows a superior performance.

Table 9
Results of the solutions by STP model, N-STP model, and R-STP model.

KPI	STP	N-STP	R-STP	Improvement of STP over N-STP	Improvement of STP over R-STP
Total Service Cost (€)	17261.8	20043	19078	16.11 %	10.52%
Fixed Cost (€)	1770	3240	2370	83.05%	33.89%
Variable Cost(€)	11332.2	10600	12473.4	−6.46%	10.07%
Transshipment Cost (€)	3344.6	4778	3344.6	42.85%	0
Earliness Penalty (€)	200	75	275	−62.5%	37.5%
Delay Penalty (€)	615	1350	615	119.51%	0
Modal split Barge (%)	34.13	57.98	29.08	−23.85	5.05
Modal split Rail (%)	49.36	11.76	48.29	37.6	1.07
Modal split Truck (%)	16.51	30.26	22.63	−13.75	−6.12
Barge services utilization (%)	44.93	83.33	39.13	−38.4	5.8
Rail services utilization (%)	85.67	22.29	85.67	63.38	0
LCS utilization (%)	62.50	57.00	59.20	5.5	3.3

We have to mention that for each replanning, the solutions and the gap between the two models depending on the network, the configuration of services and the events.

The reference N-STP model

The reference N-STP model does not allow for shipments to be split. The entire volume n^s can only be assigned to services from the same mode in each case. Each shipment is operated as one indivisible unit. One binary variable χ_a^s is used to replace the decision variables x_a^s in the STP model. If $\chi_a^s = 1$ then shipment s is assigned to arc a with the entire volume n^s. For a detailed description of the N-STP model, we refer to Appendix B. Note that, in the N-STP model, there the flexible schedules of barges and rail services are maintained for all the services.

The split of shipments gives more freedom to the flow assignment, and further promotes the loading rate of LCS via vehicle sharing. We note that this is analogous to the feature "message fragmentation and reassembly" in the Multipurpose Internet Mail Extension (Media Types), where a message is first divided into several parts and then transparently reassembled back into the original message at the recipient's end. This allows an e-mail client to improve performance when using a slow connection (because the parts are sent in parallel) as well as to circumvent size restrictions. Similarly, splitting of shipments improves the use of barge and rail services.

The reference R-STP model

The R-STP model operates the LCS according to the original schedule when dealing with perturbations. The barge and rail services depart at pre-scheduled times, while truck services maintain a flexible departure time. Thus, the flexible departure constraint (9a) of STP model is not part of the R-STP model. The reference R-STP model can be written as the object (18), constraints (1)–(10), and constraints (11)–(25). Note that, in this R-STP model, it is possible to split shipments. The corresponding solutions are shown in Table A.14.

We depict the time distance graphs of STP solutions and R-STP solutions in Fig. 8.1 and Fig. 8.2. Reader can clearly see the differences and benefits of synchronizing the service flows (barge service $v0001$) with the shipment flows (delayed shipment $S4$).

7.3. More computational tests on theoretical instances

To check the difficulties in solving the model, we first test the impact of different network sizes and shipment numbers. The indicators for the solution difficulties are indicated by the number of variables, the number of constraints, and the calculation time. The results are summarized in Table 10. The supporting data set is shared on the open data platform 4TU.Research Data. (Qu et al., 2019).

The first part of Table 10 shows that the network size has a comparatively small impact on the problem size. Meanwhile, the number of shipments has a significant effect on the problem size. This is because the model allows shipment split, which further increases the possible transshipment and the service rescheduling. The calculation is within seconds (root + branch& cut, CPU time). We indicate ticks here to illustrate the comparisons more clearly.

The above-mentioned networks are the same topology of the Rotterdam hinterland network. To further test the application of the model, we use different network typologies, including the line, ring, star, tree, and fully connected network typologies. The problem sizes are shown in Table 11.

The test shows that the STP model can be applied to all these network typologies. As shown in Table 11, the difficulties of solving the problem is not affected by the topology in question. In each case, the calculation time is also within seconds, which is compatible with the claim that the synchromodality can be used in the local network for real-time replanning. Replanning for larger networks can be divided into several sub-networks replanning problems and solved in rolling horizon fashion.

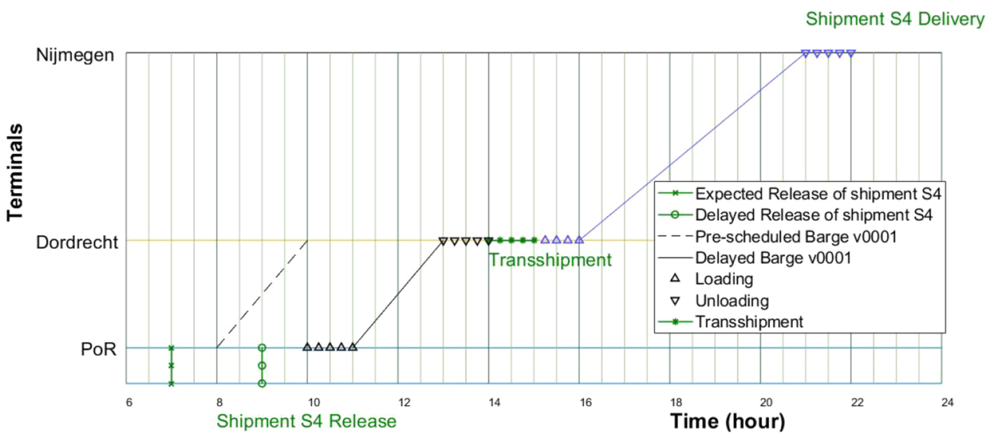

Fig. 8.1. The time distance graph of transportation of delayed shipment $S4$ by STP model.

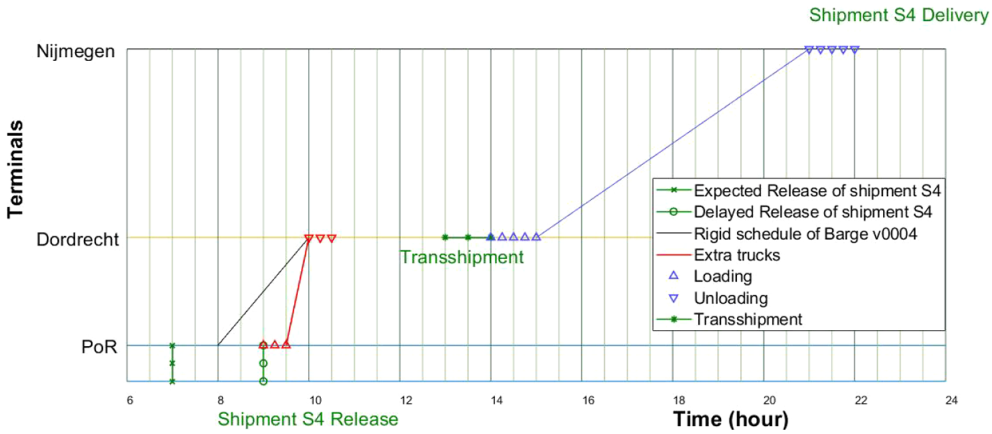

Fig. 8.2. The time distance graph of transportation of delayed Shipment $S4$ by R-STP model.

Table 10
Theoretical instances of different network size and number of shipments to test the difficulties of solving the model.

	Num of nodes	Num. of arcs (LCS+Trucks)	Num. of shipments	Num. of constraints	Num. of variables (binary, integer, other)	Calculation time* (ticks)
Network	6	6 + 600	5	7135	16412 (1722, 1106, 732)	1125.37
	7	8 + 600	5	8968	20121 (2091, 1238, 880)	203.56
	8	10+ 600	5	7558	17075 (1723, 1292, 961)	259.68
	9	12+800	5	10162	22473 (2249, 1827, 1357)	207.58
	10	14+800	5	8558	19508 (1892, 1922, 1352)	210.48
Shipments	10	14 +800	**5**	8558	19508 (1892, 1922, 1352)	210.48
	10	14 + 800	**6**	10063	23084 (2212, 2311, 1634)	261.15
	10	14 + 800	**7**	11534	26592 (2532, 2695, 1888)	367.62
	10	14 + 800	**8**	12282	28524 (2662, 3091, 2174)	566.58
	10	14 + 800	**9**	13100	30466 (2792, 3497, 2410)	442.82
	10	14 + 800	**10**	14623	34078 (3112, 3870, 2711)	774.91
	10	14 + 800	**15**	23466	53918 (4902, 5777, 3942)	882.48

Calculation time: the CPU time, include root + branch &cut.

Table 11
Theoretical instances of different network typology to test the difficulties of solving the model.

Network topology	Num. of Nodes	Num. of Arcs (LCS + Truck)	Num. of shipments	Num. of constraints	Num. of variables (binary, integer, other)	Calculation time (ticks)
	6	13 + 500	5	8152	4819 (1898, 1631, 1290)	2904.14
star	6	12 + 500	5	8139	5016 (1884, 1755, 1377)	255.76
ring	6	14 + 500	5	8478	5138 (1964, 1763, 1411)	1602.03
tree	6	13 + 500	5	7353	3727 (1613, 1157,957)	665.13
fully connected	6	12 + 500	5	6620	2320 (1547, 450, 323)	104.06

8. Conclusions and future research

In this paper, we propose a synchromodality transportation replanning (STP) model for a hinterland freight transportation network. To this end we present a mixed-integer linear programming model, determining the minimum cost solution by combining decisions integrating shipment rerouting and service rescheduling. We demonstrated the performance of the approach in the case of the Rotterdam hinterland transportation network. The STP model provides specific resolutions according to the specific perturbations those are encountered in each case. In addition, we demonstrate the benefit of synchromodality (i.e., flexibility operations in modal split and service rescheduling) compared to rigid planning and non-split shipment planning.

In this study, all the terminals involved have the ability to implement the new resolutions. However, in some cases overloaded terminals could cause delays and delay propagation. In future research, it would be interesting to include the effects of delays and congestion into the model.

Acknowledgement

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Appendix A. Original solutions and re-planning solutions

Shipments $S4$ and $S5$ are released two hours later than expected time. Table A.12, A.13, and Table A.14 correspondingly give the solutions of the STP model, N-STP model, and R-STP model.

Table A.12
STP Solution: flow assignment and the timetable.

Arc	Mode	S1	S2	S3	S4	S5	Start Time	End Time
PoR, Dordrecht, v0001	Barge		50		40		10	14
PoR, Tilburg, v0002	Rail			50		50	10	14
PoR, Nijmegen, v0003	Rail				60		14	18
Dordrecht, Nijmegen, v0004	Barge				40		15	22
Dordrecht, Venlo, v0005	Barge					50	12	23
Tilburg,Venlo, v0006	Rail					50	15	18
PoR, Utrecht,v0007-v0506	Truck	50					16	18

Table A.13
N-STP solution: flow assignment and the adjusted timetable.

Arc	Mode	S1	S2	S3	S4	S5	Start Time	End Time
PoR, Dordrecht, v0001	Barge				100		10	14
PoR, Tilburg, v0002	Rail			50			11	15
PoR, Nijmegen, v0003	Rail						not used	not used
Dordrecht, Nijmegen,v0004	Barge				100		15	22
Dordrecht, Venlo, v0005	Barge					100	12	23
Tilburg,Venlo, v0006	Rail						not used	not used
PoR, Utrecht,v0007-v0506	Truck	50					16	18
PoR, Dordrecht,v0507-v0516	Truck		50				16.5	18
PoR, Dordrecht,v0517-v0606	Truck					100	9	10.5

Table A.14
R-STP solution: flow assignment and the adjusted timetable.

Arc	Mode	S1	S2	S3	S4	S5	Start Time	End Time
PoR, Dordrecht, v0001	Barge		50				7	11
PoR, Tilburg, v0002	Rail			50		50	10	14
PoR, Nijmegen, v0003	Rail				60		14	18
Dordrecht, Nijmegen,v0004	Barge				40		15	22
Dordrecht, Venlo, v0005	Barge					50	12	23
Tilburg,Venlo, v0006	Rail					50	15	18
PoR, Utrecht,v0007-v0506	Truck	50					16	18
PoR, Dordrecht,v0507-v0546	Truck				40		9	10.5
PoR, Dordrecht,v0547-v0596	Truck					50	9	10.5

Appendix B. Reference non-split shipment transportation plannings

The reference non split shipment transportation planning can be formulated with (7)–(13), (15), (18), (19), and (21), and the following sub-objective and constraints.

$$C^c = \sum_{s\in S}\sum_{a\in A}(\chi_a^s \cdot n^s \cdot c_a); \tag{B.1}$$

$$C^e = \sum_{a\in\delta_j^-, j=d^s}(\chi_a^s \cdot \rho^{s,-} \cdot w^{s,-}); \tag{B.2}$$

$$C^{l} = \sum_{a \in \delta_j^-,\, j = d^s} (\chi_a^s \cdot \rho^{s,+} \cdot w^{s,+}); \tag{B.3}$$

$$\sum_{a \in \delta_i^+} \chi_a^s - \sum_{a' \in \delta_i^-} \chi_{a'}^s = \begin{cases} -1, & \forall s \in S,\, i = o^s \\ 0, & \forall s \in S,\, i \in N \backslash \{o^s, d^s\}, \\ 1, & \forall s \in S,\, i = d^s \end{cases} \qquad \chi_a^s \in \{0, 1\}; \tag{B.4}$$

$$\begin{aligned} &\sum_{a \in (i,j,v),\, v = rail} \chi_a^s + \sum_{a \in (i,j,v),\, v = truck} \chi_a^s = 0, \quad \text{if} \sum_{a \in (i,j,v),\, v = barge} \chi_a^s \geq 1, \quad \forall s \in S; \\ &\sum_{a \in (i,j,v),\, v = barge} \chi_a^s + \sum_{a \in (i,j,v),\, v = truck} \chi_a^s = 0, \quad \text{if} \sum_{a \in (i,j,v),\, v = rail} \chi_a^s \geq 1, \quad \forall s \in S; \\ &\sum_{a \in (i,j,v),\, v = barge} \chi_a^s + \sum_{a \in (i,j,v),\, v = rail} \chi_a^s = 0, \quad \text{if} \sum_{a \in (i,j,v),\, v = truck} \chi_a^s \geq 1, \quad \forall s \in S; \end{aligned} \tag{B.5}$$

$$\sum_{s \in S} \chi_a^s \cdot n^s \leqslant u_v, \quad \forall a = \left(i, j, v\right) \in A; \tag{B.6}$$

$$\Delta_{a,i}^{s,-} = \begin{cases} \max\left(\left(\chi_a^s - \chi_{a_2'}^s\right) \cdot n^s, 0\right) & \text{if } p_v(|p_v|) \neq i \\ \max\left((\chi_a^s - 0) \cdot n^s, 0\right) & \text{if } p_v(|p_v|) = i \end{cases}, \forall s \in S, \forall i \in N \backslash \left\{o^s, d^s\right\}, \forall a \in \delta_i^+; \tag{B.7}$$

$$\Delta_{a',i}^{s,+} = \begin{cases} \max\left(\left(\chi_{a'}^s - \chi_{a_1'}^s\right) \cdot n^s, 0\right) & \text{if } p_v(|p_v|) \neq i \\ \max\left((\chi_{a'}^s \cdot n^s - 0), 0\right) & \text{if } p_v(|p_v|) = i \end{cases}, \forall s \in S, \forall i \in N \backslash \left\{o^s, d^s\right\}, \forall a' \in \delta_i^-; \tag{B.8}$$

$$t_a^s \geqslant y_a^{arv} - \mathcal{M} \cdot (1 - \chi_a^s), \qquad \forall s \in S, \forall a = (i, j, v) \in \delta_j^+, j = d^s; \tag{B.9a}$$

$$t_a^s \leqslant y_a^{arv} + \mathcal{M} \cdot (1 - \chi_a^s), \qquad \forall s \in S, \forall a = (i, j, v) \in \delta_j^+, j = d^s; \tag{B.9b}$$

$$w_a^{s,-} = \max((\beta^s - t_a^s - \mathcal{M} \cdot (1 - \chi_a^s), 0), \qquad \forall s \in S, \forall a = (i, j, v) \in \delta_j^+, j = d^s; \tag{B.10}$$

$$w_a^{s,+} = \max((t_a^s - \beta^s - \mathcal{M} \cdot (1 - \chi_a^s), 0), \qquad \forall s \in S, \forall a = (i, j, v) \in \delta_j^+, j = d^s. \tag{B.11}$$

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