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Partial and complete replanning of an intermodal logistic system under disruptions

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ABSTRACT

The exclusive and excessive use of long-distance road transportation is not suitable way to reduce the negative environmental impacts of logistics systems. Intermodal transport, combining road with other transport modes, has the potential to reduce both operating costs and carbon footprints. One of the reasons for the low share of intermodal transport is its requirement for the coordination of scheduled transport services that can result in reducing reliability in case of disruptions due to the arrival of new shipment orders, fluctuations in shipment quantities, delays, and service cancellations within the network. This calls for reliable and efficient algorithms to replan the shipments' distribution. In this paper, the replanning problem is formulated as a path-based multi-commodity network flows. We provide two different network topologies, one of which is based on a time–space network, while the other embeds time aspect in a highly scalable alternative structure to large transportation networks. We propose a column generation method whose pricing sub-problems are presented as resource constrained shortest path problem solved via a tailored label-correcting algorithm. We look at the pros and cons of complete and partial replanning in case of disruption and provide managerial insights for intermodal networks. An extensive set of computational experiments is presented on realistic instances being generated with the consultation of our industrial partners for a logistic network including railways, waterways, and roads. The promising outcomes validate the efficiency of the proposed approach that can be easily adjusted to real-time intermodal logistic replanning.

1. Introduction

All over the world, policy makers are concerned about congestion and emissions from road transport, which is why governments in Asia, Europe and the Americas stimulate the use of other modes of transport (Zografos and Regan, 2004; Ge et al., 2020). To that end, intermodal transportation plays a central role to reach both short and long term decarbonization targets via synchronization of different modes of transport such as rail, water and road transport. Logistics Service Providers (LSPs) attempt to provide a seamless transportation service to shippers in such integrated networks by satisfying customer requirements, and reducing operational costs. Faster logistic services increase transportation costs and carbon emissions (Choong et al., 2002; Psaraftis and Kontovas, 2009; Song and Xu, 2012).

Customers abide by a mode-free booking of the LSP working under synchromodality, where price and the quality of service requirements can be selected by the user, but the transport modes for delivery is determined by the LSP (Behdani et al., 2016).

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That is to say, service providers can take advantage of choosing modes flexibly, economies of scale and the ability to respond to uncertainties in real-time. In this paper, a customer is defined as the owner of a shipment that is to be delivered from an origin terminal to its destination. An LSP company is responsible for the delivery of the customer's shipment. It organizes all transportation activities via scheduled services that can be either its own service or operated by others. Here, we follow the LSP's perspective with regard to transportation replanning.

Intermodal transportation plans are frequently impeded by a prominent obstacle facing LSPs, namely disruptions, which are irregularities in operations that require replanning (Hassan et al., 2020). The source of a disruption may vary, such as delays or cancellations on scheduled services, traffic congestion on roadway connections, etc. Short-term disruptions with effects that span less than 24 h are considered minor disruptions, while others are considered major disruptions (Qi, 2015). In this study, minor disruptions are called as disturbances and the two are used interchangeably.

Although they may be minor disruption, disturbances may render transportation plans invalid in practice. Several shipments may need to be transferred to different modes of transport when there is a serious congestion on the barge way of a terminal. Similarly, train delays may require using truck transport for several shipments to by-pass a connection and make a delivery on time. As such, disturbances can occur in real-life and could necessitate immediate replanning of shipments to be delivered by the LSPs. In this study, we develop a decision-making tool that can expeditiously tackle the replanning of intermodal logistic activities under disturbances. We treat delays and cancellations of scheduled services as disturbances. Incorporating time aspect brings additional difficulties to the planning and reduces the scalability of the problem in real-life.

Our methodology offers a remedy that can be adjusted to the real-time planning module of SYNCHRO-NET as described by Giusti et al. (2019). SYNCHRO-NET is a project consisting of multiple modules for the optimization of integrated freight transport and logistics management at strategic, tactical, operational and real-time levels. It aims to *"optimize supply chains via environmentally friendly practices in long-haul container shipments"* simultaneously, taking all stakeholders, e.g., customers, carriers, terminals, third and fourth party LSPs, into account. Our research is also in line with the work by Bock (2010), when their vehicle fleet module is replaced by container routes and adapted to real-time disturbances in an intermodal system (see Fig. 1 of Bock (2010)). Here, our focus is on replanning the flow of shipments instead of fleet management and fetches scalability for replanning in intermodal transportation networks. In the literature, road transport carbon emissions are more significant compared to railway and waterway transport, Blanco and Sheffi (2017). In addition, Mes and Iacob (2016) state that barges and trains generate less CO2 gas emissions per ton kilometer compared to trucks. The authors also mention that these modes of transport with lower CO2 gas emissions are less costly, but are also more sensitive to disruptions. Based on these studies, our framework implicitly takes both indicators into account through one cost function. The contribution of this paper is sixfold:

- An efficient transportation replanning decision tool is proposed to cope with minor disruptions in intermodal transportation networks. Our study contributes to policies described in the Sustainable Development Goals[1] by enhancing industrial information technologies, e.g., increasing the efficiency of using waterway, railway and roadway transportation networks.
- We consider two network topologies. In the first network structure, transportation activities are defined on a standard time–space network used as a benchmark. In the second network structure, we transform the network such that the time dimension is addressed implicitly, resulting in higher scalability. Our second network representation accelerates the time required to generate columns by more than an order of magnitude. To the best of our knowledge, the second network representation introduced in this work is novel and allows us to address the replanning problem at large scale efficiently.
- Existing studies rely on using a complete enumeration strategy, which becomes intractable for large networks. Our proposed column generation approach eliminates such a drawback by constructing the shipment routes on the fly and paves the way to a real-time replanning system in intermodal networks.
- The proposed approach tackles disturbances caused by delays and cancellations of scheduled services and offers fast recovery plans.
- Using the suggested decision-making approach, alternative scenarios are tested and managerial insights provided that can be applied by practitioners. In particular, we compare partial replanning, in which only the flows affected from disturbances are re-routed, and complete replanning where every shipment can be re-routed regardless of their status in regards with the disruptions to shed light on their potential financial benefits.
- Our findings imply that there is a trade-off between the severity of the disturbance and the choice of which replanning approach to use.

The remainder of the paper is organized as follows. Section 2 briefly reviews the relevant literature. We discuss the notation being used, illustrate two network structures and problem definition in Section 3. Section 4 introduces the mathematical formulation of the replanning problem and involves our solution methodology. We offer a Column Generation (CG) algorithm whose pricing sub-problem is solved by a tailored label-correcting algorithm In Section 5, we verify our findings and present our computational results. The conclusions are presented in Section 6.

2. Literature review

In this section, we classify the state-of-the-art in two parts according to the modalities used to transfer shipments i.e., single and intermodal logistic transport. Note that, in the single modal papers, one typically replans the transportation units, i.e., trains, ships and trucks, while in the intermodal case, the cargo, i.e., the containers, are replanned.

[1] https://sdgs.un.org/goals

2.1. Single-modal transport

We consider three single-modal transport options namely railway, waterway and roadway transport. Air transport is excluded since the former three are the most relevant to our study.

Railway transport. The Train Dispatching Problem (TDP) consists of routing and scheduling trains in real-time, such that no conflicts occur with other trains, while the deviations from the official timetable are minimized. Delays or cancellations in train schedules can be dealt with using decomposition techniques like Benders approach suggested by Lamorgese and Mannino (2015). The TDP only focuses on the system aspect, neglecting concerns linked to a service level. An integrated real-time train scheduling and delay management needs to incorporate service level aspects as well. For example, Corman et al. (2017) simultaneously consider traffic regulations and passenger itineraries to construct new train schedules when the original timetables are disrupted. Dollevoet et al. (2017) propose an iterative framework for real-time passenger train services planning addressing synchronized train timetabling, rolling stock and crew rescheduling for a real-case application. The aim is to find a feasible if not the best schedule, after a disruption occurs in the railway system. Metro systems are subject to real-time disruptions that may cause accumulation of passengers at platforms resulting in further delays and/or travel inconvenience. Huang et al. (2020) offer a real-time metro system planning under disruption that consists of two stages, where the first stage determines the best recovery alternative and the second stage updates train schedules.

Waterway transport. An extensive survey by Brouer et al. (2018) discusses the use of optimization methods in liner shipping covering strategic, tactical and operational level problems, such as service network design, cargo routing, vessel speed optimization, stowage planning, bunker purchasing and vessel schedule recovery. The vessel schedule recovering problem (VSRP) handles vessel schedule disruptions in container liner shipping, (Bell et al., 2013). Brouer et al. (2013) employ alternative recovery strategies such as adjusting vessel speed, omitting a port call and swapping the order of port calls in case of disruptions, which can be in the form of a delay in vessel schedules, port closures, berth space prioritization and port congestion. Vessel speed adjustments and incorporating buffer times are often used for recovering timetables in maritime service route scheduling under delays.

Roadway transport. Disruptions in roadway transportation are relatively easier to cope with than other transport modes as stated by Hrušovskỳ et al. (2021). First, roadways have more flexibility in routing as there are often multiple routes (possibly using detours etc.) available to reach a given destination in case of a disruption over a road connection. Second, the number of available vehicles, e.g., trucks, are large, and the volume or the capacity of those vehicles are small, e.g., one or two 'Twenty-foot Equivalent Units' (TEUs), in roadway transport. These cause road transport to be easier to manage than other modes when disruptions occur. A case study by Adams et al. (2012) looks at the resilience of freight networks and recovery plans for truck transportation under disruptive weather events. Truck schedules often deviate and necessitate usage of disruption management tools based on simulation, (Li et al., 2018).

The studies mentioned so far consider a single transport mode in which the transfer of the entities (cargoes or passengers), i.e., from one vessel to another, is relatively easier than it is in intermodal networks. Unlike cargo transfers, train passengers do not require an additional equipment during transfers from one train to another. Waterway transport has more commonalities with the intermodal transport networks. The transfer of cargo and the necessity of using a handling equipment during transfers are shared. However, there are multiple parties involved in intermodal networks and their synchronization is more critical, (for example, between railway operator and the seaport terminal operator) than in a single-modal transport. As such, some aspects of the single-modal transport can be used for intermodal networks, while the level of complexity is higher when multiple modes intersect.

2.2. Intermodal

In this subsection, we examine the state-of-the-art with regard to intermodality. Bock (2010) offers a real-time transportation planning model and a heuristic approach to cope with dynamic disturbances, such as vehicle breakdowns, road blockages, traffic congestion. Their focus is mostly on road transport, but also involves integrating transshipment activities between external services used by a freight forwarder and its own fleet. Random shipment demand is considered in the work by Xu et al. (2015) to solve a synchromodal transportation problem where all shipments originate from a single terminal, with different destinations. Their model is a flow-based formulation and tackled with a metaheuristic approach that integrates simulated annealing with genetic algorithm.

Zhang and Pel (2016) propose a synchromodal freight transportation framework that has capacitated service schedules with time dependent demand and supply characteristics considering transfer and transshipment of the cargo flow over paths defined by an inland service network consisting of railway, waterway and roadway transports. The authors examine the environmental and economic benefits of the synchromodal transport in terms of cost and time savings over intermodal transport, taking into account supply and demand variability.

Behdani et al. (2016) develop an MILP formulation to construct service schedules in a predefined planning period for synchromodal freight transportation. A single origin–destination pair is considered that uses barge, rail and truck transport modes without considering disruption events and delay possibility at the point of destination.

Demir et al. (2016) study an offline intermodal service network design problem to construct cargo routes and select scheduled services under demand and travel time uncertainties. The resulting problem is a tactical level problem that is solved via a sample average approximation method.

Qu et al. (2019) develop an arc-based MILP formulation that re-arranges cargo flows and schedules cargo re-routing and vessel re-scheduling. Their model integrates minor vessel schedule changes and transshipment operations of cargoes while re-routing container flows. The resulting formulation has a non-linear objective function which involves earliness and lateness of shipments as well as fixed and variable transportation transshipment costs. The main drawback of this approach is that the constructed reschedule may result in an unrealistic new transportation plan that require too many changes compared to the previous plan.

Hrušovskỳ et al. (2021) offer an integrated simulation–optimization based decision support tool for disruption management. Offline and online planning are harmonized under three recovery policies as (i) waiting at the current terminal, (ii) transshipment at the closest terminal, and (iii) using a detour route for the shipment. Our proposed model and network representations present a scalable alternative for their mathematical model to cope with disruptions.

Our problem is very much related to the synchromodality defined by van Riessen et al. (2015b) in which as a result of online intermodal planning, transport modes change in real-time. Among the above-mentioned literature, our work is closest to the work of van Riessen et al. (2015b) and van Riessen et al. (2015a). The authors design schedules for a feeder service network containing multiple transport modes and compare the effect of self-operated and subcontracted transport choices, allowing overdue shipments under different cost scenarios for transfers. Their model is a tactical level planning formulation that is a mixture of link-based flow and path-based formulations with deterministic transit times. The service frequency is a decision variable to be determined for designing service schedules and route planning of the cargoes is decided simultaneously. In this paper however, the shipments are not restricted to a single origin terminal. Unlike van Riessen et al. (2015a), we neither restrict ourselves to feeder services nor focus on schedule design by assuming that schedules of services (e.g., service frequencies) are given while overdue shipments are not allowed as part of the LSP's strategic policies.

Our proposed approach is more general in nature, in the sense that we consider delays, which do not necessarily imply a late (or early) departure, e.g., longer sailing times or congestion, which can cause delays as well, and cancellations in services. In addition, our industrial LSP partner provides not only the inland but also deep water services. This requires developing scalable algorithms tailored for larger networks. Here, we suggest an integrated Column Generation (CG) approach for replanning, instead of an independent path generation approach like the one proposed in van Riessen et al. (2015b), and offer alternative network representations for rescheduling. We observe that shipment replanning can be identified very quickly by our CG approach, which brings in a scalability that is not present in the studies mentioned, for an intermodal network.

In this study, we also look at containers as objects to be delivered on-time and provide a container-oriented network. This is different for railway transport, where train-related equipment, e.g., cars, locomotives, are usually the objects that have to be on time like parcel delivery services, such as FedEx[2] or UPS[3]. Parcel delivery services also have complex transportation networks with connections and transfers similar to an intermodal network, (Cortes and Suzuki, 2021). However, we only have a limited number of containers (objects), which are not that large compared to packages of parcel delivery services, for which there are hundreds of packages in one truck, making it impossible to replan each parcel (object). Parcel-oriented replanning is only done at the vehicle level per parcel. However, we replan in an integrated way, taking into account containers. In our problem, container replanning determines the vehicle plan, since a vehicle cannot be sent for one parcel but a vehicle, for example, a truck, can be sent for one container. In addition, we look at each container to be on time. This is a crucial difference, since there are too many packages for parcel delivery services to accomplish replanning. At a package level, this is very difficult to do for parcel delivery services whilst we can do it at the package level for container transportation. Briefly, our business model is different than the ones addressed by parcel delivery companies.

We consider a continental and intermodal network with shipments having many origins and destinations, i.e., many-to-many shipments. The LSP does not aim to construct transportation services and their schedules, and they are given. Available resources are at the disposal of the LSP under consideration and the information is shared. Our problem and resolution approach are appropriate for the business model of companies such as P&O Ferrymasters[4] or Samskip[5] which operate a European intermodal network. In that sense, this work is more challenging and different than the previous studies considering one-to-many shipments in hinterland barge networks such as in van Riessen et al. (2015a,b).

3. Problem description

Given the weekly demand of shipments and scheduled services for an LSP, the Transportation Replanning Problem (TRP) concerns finding an alternative shipment plan after a disturbance to minimize overall transportation costs. TRP is also subject to the capacity constraints of the scheduled services such that demand for shipments is met satisfying the time-windows restrictions imposed by the customers. Our framework provides a disruption management approach that can be adapted to the real-time planning of intermodal logistic systems and functions offline in the case of disturbances. For the sake of clarity, we use the terms shipment, cargo and commodity interchangeably.

[2] https://www.fedex.com/en-us/home.html

[3] https://www.ups.com/us/en/Home.page

[4] https://www.poferrymasters.com/transportation-solutions/intermodal

[5] https://www.samskip.com/

3.1. Assumptions

The assumptions based on which the problem is defined and the TRP formulated are listed as follows:

A1: Weekly demand of shipments as well as their origin and destination terminals are known.
A2: The scheduled services and their capacities as well as their departure and arrival time periods are known by the LSP.
A3: Shipments must be delivered on-time within a customer specified delivery time.
A4: The number of transshipments for every shipment is limited to at most two transshipments until its delivery.
A5: The LSP gathers near real-time updates concerning the status of the scheduled services and retrieves relevant information about the disruptions in the transportation network.
A6: The LSP is free to switch to an alternative shipment plan in case of a disruption and customer gives full authority to the LSP for the delivery of the shipment.

Assumption A1 implies that the LSP has a weekly demand information regarding the shipments. One week is also set as the length of the planning horizon. The origin and destination terminals for every shipment are given. Assumption A2 ensures that the scheduled services can be represented using the network structures introduced in Sections 3.3 and 3.4 and each Service Route (SR) as well as its planned schedules are known. Assumption A3 imposes delivery time restrictions for the customers. The LSP does not operate under a late delivery principle, so all shipments must reach the destination terminal at the specified time period set by the customer when placing the order. Assumption A4 restricts the maximum number of transshipments that can be performed until the delivery, making it possible for the LSPs to reduce transportation costs. In addition, fewer transshipment reduces the risk of disruption in the process of executing a shipment. Assumption A5 states that disruptions and their gravity are known to the LSP based on near real-time updates when they occur (location and duration of disruption). This allows the LSP to reconstruct the network and determine the new transportation plan after a disruption. Assumption A6 enables the LSP to plan its operations such that cost savings can be achieved by using of the multi-modal transportation network, whether a disruption occurs or not.

3.2. Notation

A list of notations can be found in Table 1. The second column provides the descriptions associated with each notation.

3.3. Time–space network representation

We provide two different network structures the former of which (NR1) is based on a time–space network following a discretization strategy over time. The second network representation (NR2) addresses time implicitly, hence reducing the network size. Both network structures require the solution of resource constrained shortest path (NP-hard). In this subsection, we introduce the first network structures, NR1, to represent our intermodal network.

For the sake of completeness, two basic definitions are introduced before delving into the details of the network representations. A service route (SR) consists of a given sequence of visits to terminals using a single transport mode and has at least one port-of-call through its itinerary. A scheduled service, or synonymously used as a service, is the actualization of an SR that starts its journey at a specific time. Notice that an SR and its scheduled service are different. The former defines the itinerary that is usually designed to cover as many physical terminals as possible, whereas the latter is a time-dependent realization of the SR such that each scheduled service of the SR is associated with a departure and arrival time at the corresponding port-of-calls (scheduled service).

A representative intermodal transportation network is illustrated in Fig. 1 for NR1. In the vertical axis, the terminals (physical) are represented by a square. For each scheduled service using a physical terminal, a dummy node is introduced, indicated by a circle. Time is represented on the horizontal axis and divided into $T = 11$ time periods of equal lengths. A time period t is 15 min in the figure for illustrative purposes and the length of each time period can be adjusted accordingly. Every node representing terminals and services (locations) can be connected precisely to the nodes corresponding to their destination at different time periods. Between the nodes of the same service, arcs correspond to the travelling arcs of the itinerary to reach a service node in a different time period. For physical terminals such a connection can be the same terminal in a different time period and the arcs represent waiting of the flows.

Railway, waterway and roadway connections of the services are indicated with black, blue and red arcs, respectively. Every port has at least one (or more) transport mode(s): barge, train and/or truck. Loading/unloading operations and transshipment are indicated with green dashed arcs. They connect a service node to the same physical terminal (or vice versa) indicating a loading/unloading operation. Nodes of two different services corresponding to the same terminal can also be connected via transshipment arcs, if cargo is directly transferred from one scheduled service to the other. A cargo may be transferred from a waterway service to a railway service using these arcs. Transshipment arcs are associated with the time it takes to perform the transshipment and its cost.

When a shipment has to wait at a terminal, there is a direct horizontal connection from a node at time period t to the node at time period $t + 1$ of the same terminal, which can be either a physical or a dummy terminal representing a service. Waiting arcs are indicated with a thin dotted line, which is black for physical terminals and has the same color for the service corresponding to dummy terminals representing a service node. Waiting arcs are associated with a cost value. For example, at physical terminals, this is the cost of space occupation at the terminal, which is usually incurred when a container spends more time than allowed by the terminal authorities.

Table 1
Notation.

Sets	
$\mathcal{A}$	set of arcs in graph $\mathcal{G}$
$\mathcal{D}$	set of destination nodes in graph $\mathcal{G}$
$\mathcal{K}$	set of customer shipments
$\mathcal{K}^i$	set of shipments originating from node i
$\mathcal{N}$	set of nodes in graph $\mathcal{G}$
$\mathcal{O}$	set of origin nodes in graph $\mathcal{G}$
$\mathcal{P}$	set of paths
$\mathcal{P}^k$	set of paths for shipment k
Indices	
k	shipmen
ℓ	label
o^k	origin node of shipment k
p	path
t	time period
d^k	destination node of shipment k
i	node associated with the service network
j	node associated with the service network
g	transport mode representing waterway, railway or roadway
a	an arc $a = (i, j)$ connecting node i to node j of the service network
Parameters	
b_{ij}	departure time from node i when arc (i, j) is used
c^k	travelling cost to directly sent shipment k from its origin to its destination
c^k_f	the cost of loading/unloading a unit of shipment k at a terminal
c^k_g	travelling cost rate per transportation mode g for shipment k
c^k_p	the total cost associated with path p for a unit of shipment k
c^k_{ij}	the cost of sending a unit of shipment k over the arc (i, j) from node i to node j
c^k_w	the cost of waiting (w) for a time period per unit of shipment k at a terminal
δ	duration of delay disruption
y_{pa}	binary parameter taking on a value of one when arc a is part of the path p and zero otherwise
e_{ij}	arrival time at node j when arc (i, j) is used
q^k	customer demand (in TEUs) for shipment k
t_{ij}	the travel time over the arc (i, j) from node i to node j
t^k_p	the travel time over the path $p \in \mathcal{P}^k$ for shipment k
A	the number of arcs in the graph $\mathcal{G} \equiv \|\mathcal{A}\|$
C^ℓ_i	cost weight of label ℓ for node i
H	the number of physical terminals in the transportation network
K	the number of customer shipments $\equiv \|\mathcal{K}\|$
F^ℓ_i	transshipment weight of label ℓ for node i
N	the number of nodes in the graph $\mathcal{G} \equiv \|\mathcal{N}\|$
S	the number of scheduled services
T	the number of time periods in the planning horizon $\equiv \|\mathcal{T}\|$
T^ℓ_i	transit time weight of label ℓ for node i
T^k_{max}	the maximum allowed transit time to send shipment k from its origin to destination
U	the number of nodes in a scheduled service of a service route (SR)
Decision Variables	
β^k	the flow quantity of shipment k sent directly from its origin to its destination
λ^k_p	amount of flow of shipment k over path p

Service routes are shown on the right-hand-side of Fig. 1. There are four service routes (SR1, SR2, SR3 and SR4), with a total of 15 scheduled services. SR1 starts from $i1$ visits $i2$ and ends at $i3$ with travel times of 3 time periods (45 min) from $i1$ to $i2$ and 2 time periods (30 min) from $i2$ to $i3$. SR1 is an hourly barge service and there are two scheduled services for SR1. A 15 min waiting time is added to transfer shipments at terminals, which can be extended or shortened when required. SR2 starts from port $i2$, visits $i3$ and ends at $i4$ using railway. SR2 is in service at every two time periods (half an hour) and there are five scheduled services of SR2. SR3 connects $i3$ and $i4$ via a truck service every hour and its duration takes half-an-hour so that there are three scheduled services for SR3. Lastly, SR4 is an hourly railway service from $i2$ to $i3$ taking half an hour and there are five scheduled services of SR4. Note that even when the exact departure time of a service is not the same as its associated time on the network, a connection arc can be added as long as the service arrives at its destination before the arrival time stated at the corresponding time period. Therefore, the network structure can be maintained as long as the connections satisfy the time restrictions. Otherwise, such an arc is not added to the graph.

Triangles represent the shipments to be sent over the network. A shipment k is associated with its origin o^k and destination d^k terminals. Two shipments are shown in Fig. 1. The first shipment is already at port $i1$ and has a destination of $i4$ with a delivery time of 11 time periods (165 min). The projected itinerary uses barge service SR1 from port $i1$ and transfers at $i2$ to SR2 to arrive at $i4$ using railway service. The second one is from $i3$ to $i2$ with the same delivery time restrictions. It starts at $i3$ and waits an hour

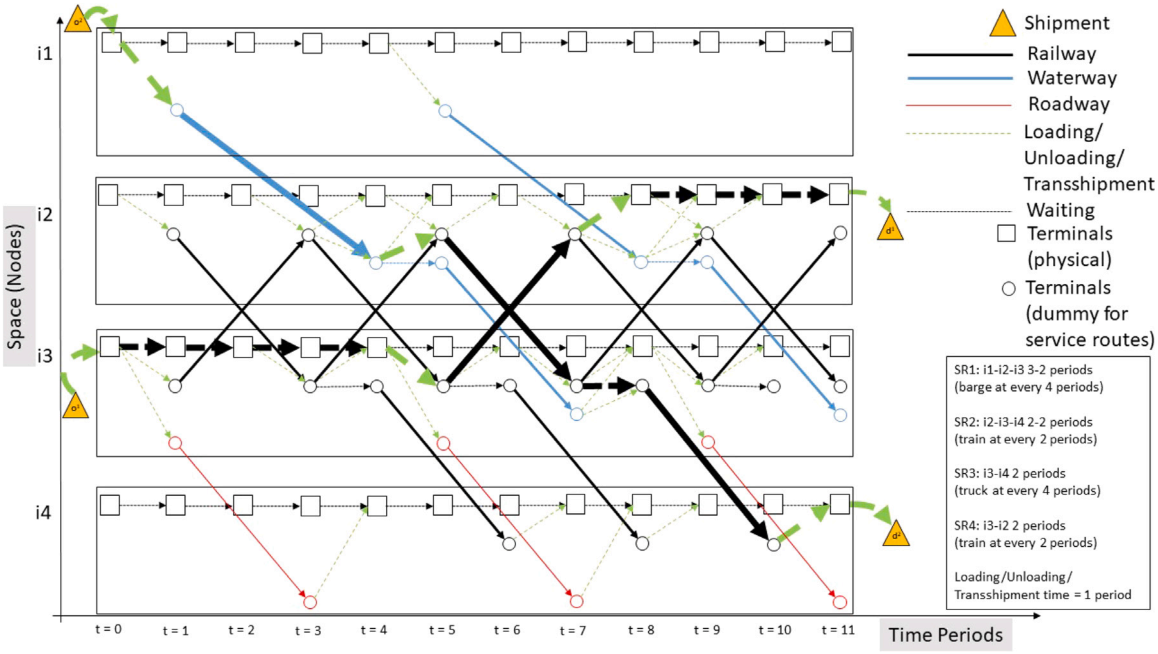

Fig. 1. Illustration of the time–space network representation, NR1.

at the physical terminal and is then loaded to railway service SR4, to arrive at $i2$. Then, it waits at $i2$ until its delivery time. The itineraries of both shipments are represented with thick arcs for the sake of clarity in the representation.

3.4. Alternative network representation

The second network representation NR2 aims to embed the time aspect of the planning by carrying it over the arcs of the network, as illustrated in Fig. 2. Here, every scheduled service is rendered by a node, indicated by with circles, with its scheduled service shown through the service route followed by a number stating its order of schedule. For example, the node labeled as SR1-2 is the second scheduled service of the service route SR1. Service routes, SR1 to SR4, are stated at the bottom right of the figure as previously stated for NR1. The nodes indicated by a square are physical terminals, each associated with a terminal's name, for example, $i1$, $i2$ in the intermodal network.

Note that service routes SR1, SR2, SR3 and SR4 are the same as in Fig. 1, with different travel duration and/or frequencies. They are also represented with the same color format, using black, blue and red colors for railway, waterway and roadway service routes, respectively. The shipment is also the same as the second shipment in Fig. 1 with origin $o^2 = i1$ and destination $d^2 = i4$ as before. Here, the planning horizon $T = 10$ (10 time periods) is assumed for simplicity.

Each arc is associated with a departure and arrival time. For example, the leftmost thick blue arc connecting $i1$ to SR1-1 has a departure at time period 0 from $i1$ and arrival at the intermediate port-of-call $i2$ at time period 3, which shows the duration to travel from $i1$ to $i2$ via waterway, using SR1. Now, the arcs connecting SR1-1 to $i2$ play the role of transshipment arcs having the departure and arrival time period 3. Therefore, the node SR1-1 can be seen as a buffer node coordinating the distribution of goods in the network.

Although the corresponding arc connects SR1-1 to $i3$, it represents the second leg of the itinerary of SR1 linking $i2$ to $i3$. This is achieved by adjusting departure and arrival times of the arc. The travel time from $i2$ to $i3$ is 3 time periods as shown for SR1 at the bottom right. Thus, the departure time of the arc SR1-1 to $i3$, is equal to the departure time of the SR1 from physical terminal $i2$, that is at time period 3. The arrival time at terminal $i3$ is equal to departure time plus the travel time (3+3) from $i2$ to $i3$, being at time period 6.

Without a loss of generality, the transshipment times are assumed to be negligible in the figure. However, they can be adjusted by assigning different values for departure and arrival time periods of the corresponding arcs. Waiting arcs, as shown in Fig. 1, are also removed in the alternative network representation NR2 in Fig. 2. When the departure time of an outgoing arc, say (i, j), from a node i is less than the arrival time of an incoming arc, say (j', i) to node i, then a flow over i is not possible using these two arcs (j', i) and (i, j). For example, consider two sequential arcs defined by SR1-1 to $i2$ and $i2$ to SR2-1. Since the flow arrives at $i2$ at time period 3 and the scheduled service SR2-1 from $i2$ departs at time period 0, such a flow is not possible using $i2$ and the shipment needs to catch a later scheduled service (represented with SR2-3) marked in orange. Now, the shipment waits from time period 3 (arrival time at $i2$) until time period 6 (departure time of SR2 from terminal $i2$).

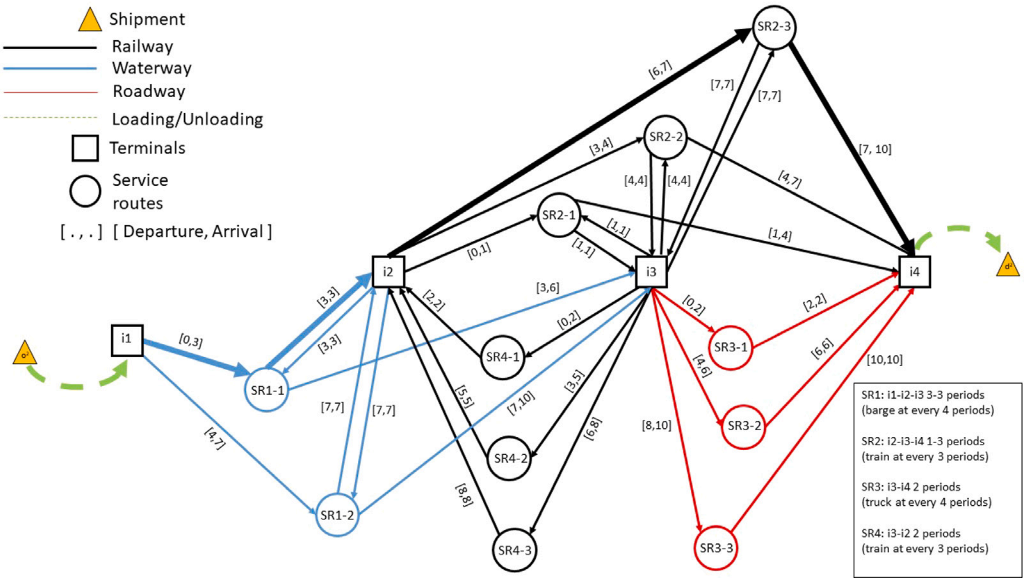

Fig. 2. Illustration of the alternative network representation, NR2.

Note that, the difference between arrival and departure time at a node constitutes the waiting time for a flow and its associated cost that can be obtained by multiplying the waiting time with the waiting cost c_w^k per period of a shipment k. An example path for the shipment, which shown with an orange triangle in the figure, can be tracked following thick arcs.

To draw a comparison between the two Network Representations (NRs) discussed in this section, we introduce additional notations. Let NR1 and NR2 denote the time–space and alternative network presentation, respectively. In our analysis, we make the following simplifying assumption to be precise. We assume that there are S scheduled services of the SRs for a given transportation network, each containing U nodes that show the visit of a vessel at a physical terminal (H physical terminals (nodes) in the network). For the sake of clarity, we exclude the dummy nodes and arcs from our analysis that should normally be added into the set of nodes $\mathcal{N}$ and arcs $\mathcal{A}$.

For the NR1, the number of nodes N and the number of arcs A in graph $\mathcal{G}$ can be simplified to the following expressions $N = T\ H + U\ S$ and $A = T\ H + 3U\ S - S$, respectively. For the NR2, these values boil down to the following: $N = H + U\ S - 2S$ and $A = 3U\ S - 3S$. Unlike the NR1, the number of nodes and arcs of the NR2 are independent from the number of time periods. Even when $T = 1$, number of nodes in the NR2 is less than the NR1 by $2S$. Such a difference is more salient for the number of arcs by $H + 2S$. This implies that computational savings can be achieved by using the NR2 instead of the classical time–space network representation (e.g., NR1). In Section 4, we present our proposed methodology to tackle the TRP based on the suggested network representations, NR1 and NR2.

4. Methodology

Once the status of the network has been defined, disturbances can be handled according to the changes. λ_p^k is the continuous decision variable showing the amount of flow for shipment k over path p. c_p^k is the total cost associated with path p for shipment k and involves the associated transportation, transshipment and waiting costs. c_p^k is calculated with respect to the network structures described in Section 3. c^k is a penalizing cost term used to make sure that the feasibility of the solution is guaranteed for each shipment k. The decision variable, β^k, associated with this penalty term c^k, is a dummy variable presenting the flow quantity that would be sent directly from the origin terminal $i \in \mathcal{O}$ of shipment k to its destination terminal. This can be considered as a direct truck service connecting the origin of a shipment k to its destination. In practice, truck services are abundantly available as mentioned by van Riessen et al. (2015b, 2016) when there is a road connection between shipment's origin and destination. Besides, in the spot market truck services are highly available with a cost trade-off similar to the penalty parameter c^k used in the second term of the objective function.

The demand for shipment k, i.e., number of containers to be shipped is indicated by q^k. u_a is the total container handling capacity on an arc $a = (i, j)$ defined by a connection from terminal i to j over the representative network. y_{pa} is the binary parameter taking a value of one when arc a is part of the path p and zero otherwise. The suggested model is a path-flow based multi-commodity capacitated network flow model given as follows:

(M)

$$\text{Minimize} \quad \sum_{k\in\mathcal{K}} \sum_{p\in\mathcal{P}^k} c_p^k \lambda_p^k + \sum_{k:i\in\mathcal{O},k\in\mathcal{K}^i} c^k \beta^k \tag{1}$$

$$\text{subject to} \quad \sum_{p\in\mathcal{P}^k} \lambda_p^k + \beta^k = q^k \qquad k \in \mathcal{K}, \tag{2}$$

$$\sum_{k\in\mathcal{K}} \sum_{p\in\mathcal{P}^k} y_{pa}\lambda_p^k \leq u_a \qquad a = (i,j) \in \mathcal{A}, \tag{3}$$

$$\lambda_p^k \geq 0 \qquad k \in \mathcal{K}; p \in \mathcal{P}^k, \tag{4}$$

$$\beta^k \geq 0 \qquad k \in \mathcal{K}^i; i \in \mathcal{O}. \tag{5}$$

The objective function (1) minimizes the total cost of the transportation. Here, the second term penalizes the flow of shipment $k \in \mathcal{K}^i$ from its origin terminal $i \in \mathcal{O}$, where $\mathcal{K}^i$ is the set of shipments with origin terminal i. Constraints (2) ensure that the demand for every shipment $k \in \mathcal{K}$ is satisfied. Constraints (3) is the capacity constraint over the arcs $a = (i,j) \in \mathcal{A}$. Non-negativity restrictions of variables are imposed by Constraints (4) and (5). Model (M) is a generic representation and maintains its validity as long as the set of paths $\mathcal{P} = \bigcup_{k\in\mathcal{K}} \mathcal{P}^k$ contains necessary paths to form the optimal solution., independent of the underlying network structure introduced in the previous section.

The model (M) support the reduction of road transportation and CO2 emissions. Mes and Iacob (2016) state that barge and trains have lower cost and CO2 emissions than the trucks per ton kilometer. This study indicates that minimizing the total transportation cost helps reducing carbon emissions. We minimize total transportation cost as an indicator of carbon emissions to benefit from the intermodality of transport modes, e.g., by taking advantage of economies of scales offered by waterway and railway transport.

Specified customer requests can be embedded within the path generation procedure to construct the required paths within the solution. For example, a customer in the network can request a specific time-window associated with shipment k. This information is known in advance when the booking is made, on the basis of which the LSP constructs the transportation plan.

The number of transshipments to be made by the shipment is also constrained, since each transshipment requires container handling operations that may create an additional risk of delay for the shipment. As defined in Constraints (3), there is a capacity limit on each scheduled service which is shared with all shipments on that service. Then, the problem reduces to finding path(s) without exceeding the capacity limits in the network and satisfying the number of transshipment and delivery time restrictions of each shipment. These restrictions can be viewed as resources and embedded within the path generation procedure.

In short, recovery after a disturbance for an existing shipment and arrival of dynamic orders can be quickly adjusted as long as the network structure is up-to-date. That is to say, changes in terms of capacity, arrival and departure times of the scheduled services are regularly updated and known. Emerging information technologies make it possible to update the existing network status almost continuously. Hence, (M) can be solved in a rolling horizon fashion whenever a disturbance occurs in the network to provide recovery plans. In the following, we provide theoretical insights when a delay disruption happens in some part of the network. Afterwards, we present the resolution approach.

Proposition 1. *If a path p of a flow under two different delay duration, δ_1 and δ_2 (when $\delta_1 < \delta_2$) is optimal, then p is also optimal for any delay duration $\delta \in [\delta_1, \delta_2]$.*

Proof. Assume that there exists an alternative path $\overline{p}$ that is also optimal under a delay duration of δ for the flow of k such that $c_{\overline{p}}^k = c_p^k$ holds. This implies that by waiting until delay duration δ, which means less waiting for a duration of $\delta_2 - \delta$, the cost for delay disruption duration δ_1 can be reduced to $c_p^k - (\delta_2 - \delta)c_w^k < c_{\overline{p}}^k = c_p^k$ which contradicts with the optimality of both p and $\overline{p}$. Thus, p is also optimal for delay disruption duration δ. □

Corollary 1.1. *There exists a threshold value δ' where the optimum path p of a flow for a delay duration δ changes when $\delta < \delta'$.*

Proof. Proof directly follows from Proposition 1. □

4.1. Resolution approach

(M) is a variant of the multi-commodity network flow problem (Ahuja et al., 1993) that can be solved by Column Generation (CG) techniques. In this section, we present a tailored CG algorithm.

Let σ^k and γ_a be the dual variables associated with constraints (2) and (3). The reduced cost of a path p of commodity k can be given as follows:

$$\overline{c}_p^k = c_p^k + \sum_{a\in\mathcal{A}} y_{pa}\gamma_a - \sigma^k \tag{6}$$

Here, $\gamma_a \geq 0$ and $\sigma^k \leq 0$ hold. Then, the optimality conditions (dual feasibility) require $\overline{c}_p^k \geq 0$ for all paths p of each commodity k and $c^k - \sigma_k \geq 0$ for $k \in \mathcal{K}^i, i \in \mathcal{O}$. For each feasible solution, the following inequality $c^k - \sigma_k \geq 0$ will be satisfied from duality conditions. Therefore, we focus on paths and their reduced costs. In case, a path p with negative reduced cost, i.e., $\overline{c}_p^k < 0$, exists for any commodity k, then path p can be used to improve the current solution and can enter the basic solution. Finding the path having the most negative reduced cost value can be achieved by solving the shortest path problem with reduced cost values for a commodity k. The cost of each arc, $\overline{c}_a^k$ $a \in \mathcal{A}$, becomes $c_a^k + \gamma_a$ and the shortest paths are determined using $\overline{c}_a^k$ values.

New columns are generated until there is no negative reduced cost path p for a commodity k, i.e., $\bar{c}_p^k \geq 0$ for all $p \in \mathcal{P}^k, k \in \mathcal{K}$. Additional stopping conditions can be used to accelerate the CG procedure. A lower bound z_{LB} can be defined on the optimal solution value z^* of (M). Then, the CG procedure can be stopped when the current solution value deviates within a predetermined percentage from the optimum value. Let z_{UB} be the upper bound value of (M) at an iteration of the CG algorithm. We define $\xi^k = \min_{p \in \mathcal{P}^k} \{\bar{c}_p^k\}$. Then, the following result holds.

Proposition 2. *$z_{LB} = z_{UB} + \sum_{k:\xi^k<0} \xi^k q^k$ constitutes a valid lower bound on z^*.*

For the sake of brevity, the proof of the proposition is not presented, since it is very similar to the result by Holmberg and Yuan (2003). In Proposition 2, $z_{LB} \leq z^*$ and z_{LB} is useful to check the proximity of the current solution value, e.g., the upper bound z_{UB} at that iteration, to the lower bound z_{LB} during the CG iterations. Such an approach avoids the excessive generation of new columns and thus accelerates the CG algorithm. Consequently, the CG is stopped when the following inequality holds: $\frac{z_{UB}-z_{LB}}{z_{LB}} \leq 0.001$.

4.2. Pricing subproblem

(M) implicitly considers delivery time and/or the number of transshipments required for the shipments within the paths. These are additional constraints on the structure of paths that need to be satisfied, which means the CG algorithm works as described. However, the resulting pricing subproblem becomes a Resource Constrained Shortest Path Problem (RCSPP) under delivery time and/or transshipment constraints. RCSPP is an NP-complete by reduction from the shortest weight-constrained path problem (Garey and Johnson, 1979). Fortunately, RCSPP can be solved in pseudo polynomial time using a generalization of the algorithm by Holmberg and Yuan (2003) which modifies the initially proposed algorithm by Desrochers and Soumis (1988) for the shortest path problem with time windows.

Here, we adjust their algorithm such that multiple resources are addressed, e.g., maximum delivery time and/or number of transshipment. Note that our first network representation (NR1) uses the maximum number of allowed transshipments as a resource. The proposed discretization strategy over time automatically allows for addressing the maximum delivery time restrictions by adjusting the dummy arcs connecting the physical terminal node to the destination node representing the shipment, see Fig. 1. Our second network representation (NR2), on the other hand uses both maximum delivery time and the number of transshipments as resources. The structure also requires checking the feasibility of a connection, especially at physical terminal nodes, due to arcs having a time window; e.g., departure and arrival time periods.

Label-correcting algorithm constructs labels for the nodes of the graph. Labels are updated taking dominance relationship into account, such that only the non-dominated labels for a node are allowed to proceed to the next iteration. The algorithm finds at least one path between origin and destination nodes satisfying maximum delivery time and/or transshipment constraints.

Algorithm 1 presents the label-correcting algorithm that is applied to both network structures yielding the shortest path for commodity k. However, we emphasize different aspects of the algorithm for both network structures, since the algorithm changes slightly for each network structure. In Fig. 1 for the NR1, the connections of the triangle nodes, representing a shipment is loaded (unloaded) at the origin (destination) terminal, are limited to the physical terminal that is feasible with respect to the delivery time. Notice that each physical terminal node (square nodes in Fig. 1) is associated with a time period. Then, a physical terminal node with a time period that is later than the delivery time of the shipment is not connected to a triangle node by construction. Therefore, delivery times are not required to be explicitly checked during the label-correcting algorithm. So the labels for the first network representation NR1 does not require checking the delivery time restrictions as mentioned. Hence, T_i^{ℓ} can be removed from the labels ℓ. As a result, the left term $T_i^{\ell^*} + t_{ij} \leq T_{max}^k$ in the "if" statement in line 6 is dropped for NR1. Accordingly, the term $T_i^{\ell^*} + t_{ij} \leq T_j^{\ell'}$ in line 7 and the term $T_i^{\ell^*} + t_{ij}$ in line 10 also cancel out from Algorithm 1 when NR1 is used.

These modifications are caused by the structure of NR1 and how it handles the delivery time restrictions by construction as described. On the other hand, for the second network representation NR2, an additional control, to check the validity of the arrival time at node i of a label ℓ and possible connections from node i, i.e., $\{(i,j) : j \in \mathcal{N}_i\}$, is needed. T_i^{ℓ} can be considered as the arrival time period at node i of label ℓ. In line 6, an additional condition must be satisfied so that the arrival time at node i is less than or equal to the departure time b_{ij} over the arc (i,j), i.e., $T_i^{\ell^*} \leq b_{ij}$. Otherwise, such a connection is not valid for an itinerary and can be ignored from the set $\mathcal{N}_i$. The rest of Algorithm 1 remains the same as a given for the second network structure. The following proposition shows that when the capacity restrictions over the scheduled services are not strict, finding the RCSPP's solution for the affected shipments is sufficient.

Proposition 3. *When there is sufficient capacity over the arcs of available scheduled services after a disruption occurrence, solving the RCSPP for the affected shipment flows yields the new optimal planning.*

Proof. Let p be the path of a shipment flow λ_p^k before a disruption. By construction, the RCSPP finds the minimum cost path $\hat{p}$ for this flow such that $\lambda_{\hat{p}}^k = \lambda_p^k$ aftermath a disruption where some arcs are excluded from the graph $\mathcal{G}$. This implies that when there is sufficient capacity over the arcs of $\hat{p}$ after a disruption, there is no path with lower cost. Repeating this for each shipment flow concludes that the new plans using the routes from RCSPP is optimal. □

Algorithm 1: The label-correcting algorithm to solve the RCSPP for a commodity k

1 Input: Origin node o, destination node d, graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, cost weights c_{ij}^k ;
2 *Initialization:* $C_o^\ell = 0$, $T_o^\ell = 0$, $F_o^\ell = 0$, $\mathcal{L} = \{C_o^\ell, T_o^\ell, F_o^\ell\}$, $\mathcal{L}^o = \mathcal{L}$, $\mathcal{L}^i = \emptyset$ for all $i \in \{\mathcal{N} \setminus o\}$ and $\mathcal{Q} = \emptyset$;
3 *Label Selection:* Select a label $\ell^* = \underset{\{\ell \in \mathcal{L}^i : i \in \mathcal{N}\}}{lex\ min} \{C_i^\ell, T_i^\ell, F_i^\ell\}$. If there is no such a label such that $\mathcal{L} = \emptyset$, then stop, backtrack using $\mathcal{Q}$ and report the shortest path p^* ;
4 *Label Correction:* Set $\mathcal{N}_i = \{j : (i,j) \in \mathcal{A}\}$.
5 **for** $j \in \mathcal{N}_i$ **do**
6   **if** $T_i^{\ell^*} + t_{ij} \leq T_{max}^k$ *and* $F_i^{\ell^*} + f_{ij} \leq F_{max}^k$ **then**
7   **if** $\exists$ *a label* $\ell' \in \mathcal{L}^j$ *such that* $C_i^{\ell^*} + \bar{c}_{ij}^k \leq C_j^{\ell'}$ *and* $T_i^{\ell^*} + t_{ij} \leq T_j^{\ell'}$ *and* $F_i^{\ell^*} + f_{ij} \leq F_j^{\ell'}$ **then**
8             $\mathcal{L}^j = \{\mathcal{L}^j \setminus \ell'\}$ and $\mathcal{L} = \{\mathcal{L} \setminus \ell'\}$;
9 **if** *Step 7 holds for at least one label* **then**
10   Construct a new label $\bar{\ell} = \{C_i^{\ell^*} + \bar{c}_{ij}^k, T_i^{\ell^*} + t_{ij}, F_i^{\ell^*} + f_{ij}\}$, associate label ℓ^* of node i as the preceding label of $\bar{\ell}$ and set $\mathcal{Q} = \{\mathcal{Q} \cup \bar{\ell}\}$;
11   **if** *Node of* $\bar{\ell} \neq d$ **then**
12   Set $\mathcal{L} = \{\mathcal{L} \cup \bar{\ell}\}$ and $\mathcal{L}^j = \{\mathcal{L}^j \cup \bar{\ell}\}$;
13 Go to Step 3.

Complete versus partial replanning. The model (M) and Algorithm 1 proposed are general and suit for both replanning and planning problems. This can be considered as a strength of our modeling approach. When there is no disruption in the network or at the beginning of the planning horizon, model (M) can be solved to prepare shipment plans for initial transportation planning. Replanning needs to be done when a disruption occurs. A relevant idea is to update the transportation network, e.g., connections and their capacities in the graph, and resolve the corresponding model (M) again for such a replanning. We name this replanning approach of solving model (M) from scratch at every disruption event as "complete replanning". In complete replanning the model (M) is solved after updating the network representation depending on the type of the disruption. When a scheduled service is cancelled, the corresponding arcs are removed from the network representation and model (M) is solved afterwards. When a scheduled service is delayed, the delayed arcs are replaced with new arcs corresponding to a later time period reflecting the delay in the network representation and then the model (M) is solved. In that sense, complete replanning and initial planning problem are similar to each other. Proposition 3 paves the way to for an alternative replanning approach that can be performed very quickly. Indeed, it is not necessary to solve (M) every time for replanning. When a disruption has minor effects on the network and there is sufficient capacity to carry on the affected shipment flows, Proposition 3 implies that solving RCSPP, e.g., using Algorithm 1, is sufficient to construct the new transportation plan. On the other hand, it is also possible that the minimum cost paths found in the disrupted network after a disturbance can coincide with existing shipment flows, where a decision whether to replan all shipment flows or to re-route only the affected flows, has to be made. The former replanning is the mentioned "complete replanning". The latter is called as "partial replanning" in the sequel and (M) is solved only for the affected shipment flows aftermath a disruption. In partial replanning, the network update requires additional effort. In addition to the updates described for complete replanning, the capacity of the service arcs are updated such that unaffected cargo flows of the initial planning problem are subtracted from the corresponding arc capacities. Then, model (M) is solved on the resulting reduced problem. Fortunately, partial replanning involves solving only a RCSPP for each affected shipment flow as long as Proposition 3 holds. Besides, it updates the transportation plan such that the resulting replan has the least change over the previous plan. Briefly, both replanning and planning problem require efforts to solve model (M) on different networks which are perturbed after a disruption. We present a detailed analysis addressing the pros and cons of complete and partial replanning approaches in Section 5.

5. Computational experiments

In this section, we evaluate the performance of our proposed approach with regard to complete and partial planning. We also examine the managerial implications of the resolution approach using different disruption scenarios. Model (M) associated with our proposed CG algorithm is solved by Gurobi 9.1.1. The results are generated on a PC with i7-9750u 2.60 GHz processors and 16 GB RAM operating within 64-bit Microsoft Windows 10 environment. We use Julia programming language v1.5.0 combined with JuMP package.

A base scenario, namely S0, is first described in Section 5.1 for our computational experiments. The transportation plan obtained from S0 constitutes a baseline for comparison with the remaining scenarios under disturbances. These include disturbance scenarios of service delays (S1) and service cancellations (S2) as explained in Section 5.2. We compare complete versus partial plan update using different disturbance scenarios in Section 5.3. We discuss the impact of replanning and derive managerial insights in Section 5.4. Our additional experiments in Section 5.5 show that the proposed methodology is promising to cope with large instances for replanning.

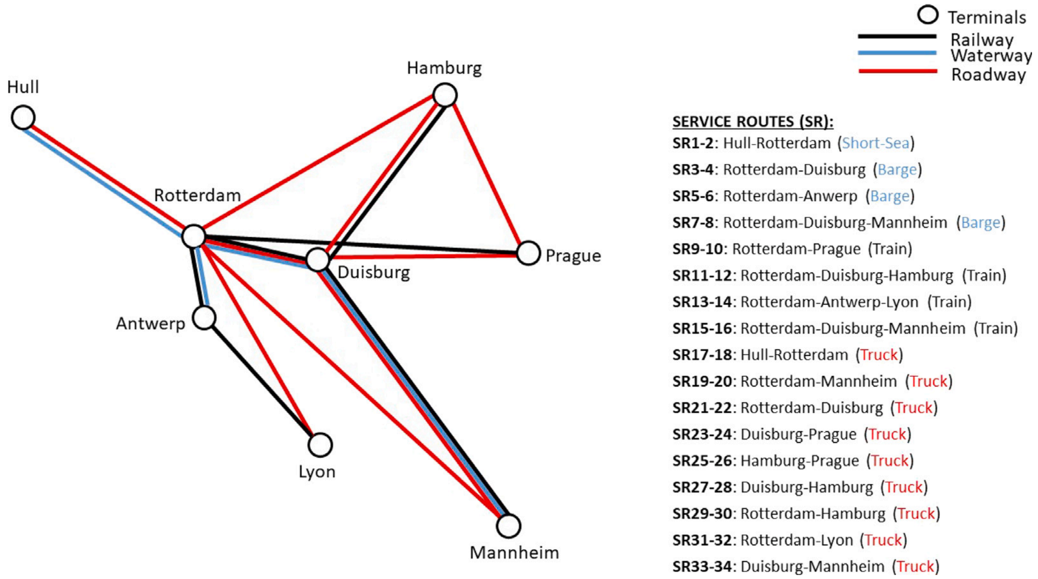

Fig. 3. Intermodal service network.

5.1. Base scenario

We introduce a European intermodal transport network consisting of processing terminals connected to each other via railway, waterway and/or roadway services. The service network shown in Fig. 3.

This network mimics part of the intermodal network of P&O[6]. In this logistics network, there are eight physical terminals and 34 service routes (see Table B.9 SR1 to SR34). Notice that, the resulting NR1 and NR2 representations of this network are difficult to visually depict. Therefore, Fig. 3 is simplified for a better comprehension of the network. To that end, connections are only placed when there is a service route between two terminal nodes and their colors represent the corresponding transport mode similar to Figs. 1 and 2. There are 96 scheduled services for railway and waterway SRs in the network. Each scheduled service and hence every arc in the corresponding NR1 and NR2 have its own capacity. The capacity of the arcs are shared among all shipments that are using the same scheduled service. The number of scheduled services corresponding to roadway is equal to 558 yielding a total number of 654 scheduled services. However, roadway (or truck) connections are used to show the availability of an alternative transport mode for the recovery and the completeness of the network representation to solve (M).

The network shown in Fig. 3. The planning horizon is equal to $T = 168 \div 2 = 84$ time periods. One week consists of $7 \times 24 = 168$ hours and each time period contains two hours. The connections are denoted with undirected arcs whose colors indicate the transport mode (waterway, roadway and railway) in blue, red and black, respectively.

The terminals are presented in circles that also include their names. SRs are assumed to be symmetric. For example, SR1-2 states that SR1 is from Hull to Rotterdam, while SR2 is the other way around. A summary of the SRs is given in Table B.9. For the sake of brevity, only odd numbered SRs are given and even numbered SRs can be derived using the symmetry property by reversing origin–destination for each pair.

In Table B.9, the first column states the name of the SRs, while the second column represents the information of the SRs. The legs of the itinerary are denoted by an arrow symbol "$\longrightarrow$" connecting two port-of-calls on its left and right, while the duration of travel in number of time periods for the corresponding leg is mentioned above the arrow. Column 3 states departure time periods with the associated scheduled service.

For example, SR1 provides services with departure times at time periods $\{1, 25\}$, which corresponds to a service scheduled at the first and third day of each week, starting from midnight on Mondays with a travel time of 15 time periods (30 h) to arrive in Rotterdam. Note that, symmetry property holds in both directions of the SRs. Column 4 stands for the capacity of the SRs. The last column shows the transport mode of the SR as 'Waterway', 'Railway' or 'Road'. For transport by road, there are no capacity restrictions.

Travel time between any pair of terminals is computed using an online calculator[7] to derive shipment route and its associated travel time for a single shipment. Only direct connections are considered and transfer times are calculated based on drop-off and pick-up times specified on the same website. These times are included in the travel times for each service route. Notice that, in

6 https://www.poferrymasters.com/transportation-solutions/intermodal

7 https://rotterdam.navigate-connections.com/voyages

Table 2
Unit transportation costs, (van Riessen et al., 2015b).

Transport Mode	Cost per unit flow
Barge/Short sea	$0.14 \cdot distance$ (km)
Rail	$1.53 + 0.16 \cdot distance(km)$
Truck	$76.4 + 1.04 \cdot distance(km)$

practice, travel times may vary depending on the departure time as well as different operators of the service could mandate shorter or longer travel times especially for waterway connections. Here, we have chosen the fastest (when applicable) of those scheduled services in terms of travel times for simplicity and assumed that every scheduled service of the corresponding service route would have the same travel time. Nevertheless, our methodology is generic and can be applied when different scheduled services have different travel times without loss of generality.

A set of shipments, $\mathcal{K}$, is routed among these network terminals so that every shipment $k \in \mathcal{K}$ satisfies the customers' transit time requirements, namely $t_p^k \leq T_{max}^k$ for each $p \in \mathcal{P}^k$. The origin and destination terminals of the shipments are randomly chosen among the pairs of terminals. 10 commodities are randomly generated with the demand size being selected from a given interval $[100, 200]$ as a multiple of ten. The shipments are assumed to be available at the first time period and each has a delivery time restriction of 140 hours. Arc capacities in the network are set to 80 and 40 units of flow for waterway and railway (see Table B.9).

Roadway connections are assumed to have unlimited unit flow capacity. One unit flow is generic in our setting and it can be defined as one 'Twenty-foot Equivalent Unit' (TEU), two TEUs or one trailer depending on the application. Other arc capacities, e.g., loading/unloading arcs, waiting arcs and dummy arcs for arrival of shipments to the physical terminals, are unbounded.

Cost parameters associated with the arcs on the network are also borrowed from the work by van Riessen et al. (2015b). The loading/unloading cost of one unit of shipment k is set as $c_f^k = 24$ and is the same for each transport mode. Similarly, costs associated to waiting arcs are assumed to be at a symbolic rate of $c_w^k = 1$ per time unit for every shipment. This reflects holding cost at container terminals and avoids unnecessary waiting of the shipments at the terminals which may result in undesirable paths being constructed.

The travel cost values are calculated based on Table 2 using the cost data as is. The average speed per transport mode to connect nodes i and j, i.e., for finding c_{ij}^k values, are assumed to be 12, 30, and 60 kilometers per hour for waterway, railway and roadway services, respectively. It is worth mentioning that the connections on the network given in Figs. 1 and 2 are present only when a vessel could arrive at the destination earlier than the departure time period without loss of generality.

The output of model (M) on the base scenario S0 constitutes the original transportation plan. Disturbance scenarios S1 and S2 are then compared with S0 as a baseline. The CG algorithm requires to find an initial solution. To that end, we first add dummy arcs to the graph $\mathcal{G}$ for each shipment on the network representation to directly connect the origin and the destination of the shipments. These arcs have unlimited capacity but they have a high penalty cost of 10^6, e.g., for c^k values associated to β^k variables. Then, a column for each shipment is added in the initial solution of model (M) using these arcs. The corresponding paths consist of only one arc using one of these dummy arcs representing shipment k. Initially, each shipment flows through these dummy arcs with high penalty values and thus Algorithm 1 does not have to be solved at the beginning of the CG procedure. However, the flow values over these dummy arcs are enforced to be zero during the CG procedure, which uses the dual values obtained after solving the model (M), and solves the pricing subproblem by Algorithm 1. Then, the iterations repeat until there is no path with negative reduced cost. Therefore, adding these dummy arcs guarantees that (M) is always feasible even when a disruption occurs. Consequently, the remainder of our analysis is based on the solution of S0 and the objective function values for disruption scenarios S1 and S2 whose outputs can deviate from the base scenario S0.

The overall performance of the intermodal network is measured using the total cost of the delivery plan and the percentage of flows over different transport modes. For total cost, the objective function (1) can be used directly. For percentage of flows, the following formula is used.

$$TM(g) = 100 \times \frac{\sum_{k \in \mathcal{K}} \sum_{p \in \mathcal{P}^k} \sum_{a \in \mathcal{A}} y_{pa}^g \lambda_p^k}{\sum_{k \in \mathcal{K}} q^k} \tag{7}$$

where $TM(g)$ stands for the percentage of flow carried over transport mode $g \in \{1, 2, 3\}$. Here, $g = 1$, $g = 2$ and $g = 3$ indicate transport modes for waterway, railway and road, respectively. y_{pa}^g takes a value of 1 when arc a is part of path p for transport mode g.

Total costs and $TM(g)$ provide an overview of the current status of the network. We consider three shipment-specific Performance Indicators (PI) to gain more insight into how disturbances affect the intermodal network. These three PIs show the relative change of plans with respect to the base scenario S0.

The *first PI* is the percent of Flows Re-routed (FR) when compared to S0. To that end, all paths of a shipment k used for S0 are compared to the new paths of the shipment after a disruption, S1 and S2. When there is a flow that uses other paths than the case for S0, it is considered as being re-routed. Then, the sum of the re-routed flows of a shipment k is divided by the total demand for k and FR shows the percentage of change for each shipment.

The *second PI* represents average unit shipment Cost Change (CC) from S0. The average unit shipment cost $ASC^{S0(k)}$ for shipment k in S0 is calculated as $ASC^{S0(k)} = \frac{\sum_{p \in \mathcal{P}^k} c_p^k \lambda_p^k}{q^k}$ where λ_p^k denotes the flow of shipment k over a path p for S0 and c_p^k is the cost of using path p for shipment k. The ASC value after a disruption is calculated similarly as $ASC^{S(k)}$ for $k \in \mathcal{K}$ where S could be any disruption scenario. Now the CC of disruption S is determined as $CC^k = \frac{100\times(ASC^{S(k)}-ASC^{S0(k)})}{ASC^{S0(k)}}$ for each shipment k. CC^k can be either positive or negative, depending on the overall structure of flows and disturbances. When a bottleneck arc has some extra capacity after a disruption occurs in some parts of the network, it may be filled up by another shipment k that is unaffected by the disruption. Thus, unit shipment cost for shipment k can be lower than before the disruption occurred. On the other hand, we can expect that the unit shipment cost of shipments affected by a disruption is likely to increase.

The *last PI* measures the deviation of Modal Split (MS) between the base scenario $S0$ and a disruption scenario per shipment. To calculate MS, first the $TM(g)$ values are computed both for $S0$ and the disruption scenario S, say $TM(g)^{S0}$ and $TM(g)^S$ for each transport mode $g \in \{1,2,3\}$ as described. Now, MSC^k is the modal split change per shipment k and is defined by the following vector $MSC^k = [TM(1)^{S0}-TM(1)^S, TM(2)^{S0}-TM(2)^S, TM(3)^{S0}-TM(3)^S]$. Elements of MSC^k could be positive or negative, thus, we use standard deviation, e.g., $std(.)$, to represent the modal split change after a disruption. To summarize, $MS^k = std(MSC^k)$ is set for each shipment $k \in \mathcal{K}$.

Benchmarking Approach: The work by van Riessen et al. (2015b) presents a complete enumeration scheme to solve a similar problem to TRP which works for a hinterland network with one port as origin, but not for a many-to-many network, because of its low scalability. Considering the size of the network operated by a continentally operating LSP, real-life instances would exceed the capability of enumeration strategies. However, we have incorporated such an enumeration approach for comparison purposes using the paper by van Riessen et al. (2015b). Note that TRP is different from van Riessen in the sense that it does not allow late deliveries. Therefore, we have calibrated the enumeration strategy accordingly for our proposed framework. The benchmarking approach is represented with 'BA' in the sequel compared with our base scenario S0 whose details are described in Section 5.2.

5.2. Disturbance scenarios

We consider two different scenarios based on S0 under disturbances. We discuss the details associated with these two scenarios: service delays (S1) and service cancellations (S2). Roadway is both the most expensive (per transport unit per distance) and the most accessible (i.e., with flexible departure times and dense network connectivity) transport mode compared to waterway and rail (Hrušovskỳ et al., 2021). Therefore, in our analysis, we address only the disruptions that occur on waterway and railway SRs. Unlike waterway and railway SRs, road services can be easily compensated in case of a disruption from the spot market where there often exists an alternative.

Service delay (S1). Scheduled services are subject to delays. In scenario S1, a scheduled service is assumed to have a delay for a duration up to 12 h (6 time periods) between two scheduled services of the same service route. Hence, different delay durations can be considered as sub-scenarios such that a delay duration of $\delta \in \{2,4,6,8,10,12\}$ hours is examined. This is repeated for every scheduled service of each service route for different delay durations δ as mentioned. Then, the average obtained over all scheduled services of the service routes for one particular delay duration (e.g., 8 h) is calculated and reported. It is assumed that the corresponding service would be cancelled if it goes beyond 12 h of delay. Here, only one disturbance (e.g., for a given delay duration δ) of a scheduled service is assumed to occur during the entire planning horizon in one week. Replanning updates can take place at upon each disturbance occurrence while replanning can be repetitively applied for the upcoming disturbances within one week thereafter. Then, the suggested methodology is performed in a rolling horizon fashion that does not cause loss of generality for addressing more than one disturbance in a week.

Service cancellation (S2). Service cancellations are considered in a similar way to S1. In scenario S2, each scheduled service is assumed to be cancelled one at a time. The results are averaged over the cancelled scheduled services. Note that the service cancellations have a more severe impact on the network than service delays. They constitute the worst case bound on the disturbance outcome when compared to the delay disturbance of the same service.

5.3. Partial vs complete replanning

In this section, we compare two planning approaches based on the performance indicators described in Section 5.1. For the partial replanning approach, it is assumed that the flows that are affected from a disruption are replanned, and then recovery plans are constructed only for those flows without changing the shipment plan of unaffected flows. Whereas, in the complete replanning approach, it is assumed that the LSP can re-route any shipment flow regardless of whether a shipment flow is affected by disruption. As a result, a complete replanning approach gives more flexibility to the planner to possibly benefit from economies of scale. However, implementing several changes requires longer computations. Here, we first present our results on service delay disturbances S1. Then, we show the results associated with the service cancellation disturbances S2.

In Table 3, represented for S1 are obtained as the average of a delay disruption taking every scheduled service of the network into account. The results are collected for each delay duration mentioned. The third column represents the output of the base scenario S0. Columns 5 to 8 contain the results on partial replanning. Complete replanning is found in the last four columns of the table. The third row stands for the duration of the disruption in hours (hrs). Delay duration of 2, 4 and 6 h are combined to be precise since their results are the same.

For the remaining delay duration of 8, 10 and 12 h, we observe changes in the outcomes. The objective value is given in the fourth row as "Total Cost" for each delay duration. Rows 5 to 7 present the percentage of flows using waterway, railway and roadway transport modes as given in (7) that are shown with $TM(1)(\%)$, $TM(2)(\%)$, and $TM(3)(\%)$, respectively. We provide detailed computational performance of the two network representations NR1 and NR2 presented in Section 3.3 and in Section 3.4,

Table 3
Summary of results for partial vs complete replanning under service delays (S1).

		S0	BA	S1							
				Partial replanning				Complete replanning			
	Duration			2 to 6 h	8 h	10 h	12 h	2 to 6 h	8 h	10 h	12 h
	Total Cost	374360	374360	374405.22	374606.96	375083.48	462084.35	374405.22	374565.22	375041.74	375459.13
	$TM(1)(\%)$	44.12	44.12	44.12	44.12	44.12	44.22	44.12	44.03	44.03	44.05
	$TM(2)(\%)$	38.97	38.97	39.03	38.97	38.91	38.74	39.03	39.07	39.01	38.97
	$TM(3)(\%)$	16.91	16.91	16.85	16.91	16.98	17.05	16.85	16.9	16.96	16.98
NR1	Total CPU (s)	62.76	140.47	1.38	1.41	1.41	1.50	49.88	50.52	51.34	51.87
	Model (M) CPU (s)	7.18	17.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
	Alg. 1 CPU (s)	50.3	123.19[a]	0.87	0.90	0.90	0.99	49.50	50.15	50.96	51.48
	# of path calls	60	1[b]	2.00	2.04	2.04	2.04	60.14	60.87	61.74	62.17
	# of columns added	37	112302	1.00	1.04	1.04	1.09	37.04	37.35	37.52	37.52
NR2	Total CPU (s)	15.53	288.21	0.31	0.31	0.31	0.31	3.18	3.12	3.15	3.16
	Model (M) CPU (s)	7.24	20.90	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01
	Alg. 1 CPU (s)	3.29	266.52[a]	0.04	0.04	0.04	0.04	3.11	3.05	3.08	3.09
	# of path calls	70	1[b]	2.03	2.04	2.00	2.00	68.70	67.83	67.83	67.83
	# of columns added	38	367899	1.16	1.17	1.13	1.13	38.10	38.09	38.04	38.00

[a] Implies the total running time to construct paths by the BA. Algorithm 1 is not applicable for this value.
[b] Enumeration of paths is done once at the beginning in BA.

respectively, in the remaining rows. Here, "Total CPU (s)" is the total CPU time in seconds. "Model (M) CPU (s)" and "Alg. 1 CPU (s)" respectively represent the time spent to solve the corresponding linear programs and the pricing subproblem using Algorithm 1 in seconds. Note that, total CPU is higher than the sum of model (M) and Algorithm 1 CPUs due to additional mathematical operations within the code. The row indicated with "# of path calls" show the number of times Algorithm 1 is called during the CG procedure. Not every path generated by Algorithm 1 has a negative reduced cost and only those paths with negative reduced cost can be added to Model (M) as new columns. Thus, the row "# of columns added" indicates the number of columns added to the model (M) during the CG procedure. As a remark, the values for "Alg. 1 CPU (s)" and "# of path calls" are different for the BA. Algorithm 1 is not used and the paths are generated by complete enumeration only once at the beginning. Therefore, we report the time to generate the paths by enumeration and the corresponding value of "# of path calls" is set as 1. These values are marked with † and ‡ and mentioned at the bottom of the Table 3.

5.3.1. Analysis of partial vs complete replanning under S1

In Table 3, we observe that total cost increases as the duration of the delay does. Shorter delays cause low discrepancy from the base scenario, S0. On average, the total transportation cost of partial replanning is always higher than or equal to complete replanning. For a delay duration of 2 to 6 h, both replanning approaches have the same average transportation costs, while the difference becomes more visible (e.g., more than 20%) for 12 h of delay. Statistically, the effect of delays using partial replanning on the transportation costs are not significantly different than those of the complete replanning. We have performed a paired t-test to determine whether partial planning is different from the complete replanning. For each delay duration (e.g., 2 to 6 h, 8 h, 10 h and 12 h), a t-test is applied on their differences at a significance level of $\alpha = 0.1$ from which the p-value was always higher implying that cost-wise partial and complete replanning yield similar outputs.

Solving model (M) is almost insignificant for both partial and complete replanning. The majority of the running times are spent to solve the pricing subproblem and thus to run Algorithm 1. Both the average total CPU and the number of columns added for partial replanning are much less than the complete replanning since partial replanning only addresses the affected shipments. We observe that the number of columns added to model (M) is usually less than three for the partial replanning and this value is more than 37 for the complete replanning in the average. This also indicates that partial replanning minimally modifies the initial transportation plan aftermath a disruption. Although the number of columns added are slightly higher than the base scenario S0, complete replanning can be solved faster than the base scenario S0. Both partial and complete replanning yields even better results with the NR2 than the NR1. CPU times indicate that the time–space network representation NR1 can be solved significantly slower than the alternative network representation NR2 for replanning. Nevertheless, both NRs can be solved in less than a minute for partial and complete replanning in the cases considered.

As for the benchmarking approach described at the end of Section 5.1, the results are also shown in the fourth column of Table 3. We observe that the solution times and the generation of paths can be prohibitive with complete enumeration using both network representations (NR1 and NR2) compared to our CG algorithm. This confirms the usability of both NRs in real-life disturbance events based on our experiments.

We see that transport modalities, representing the percentage of flows using waterway, railway and road transport as given in (7), stated by $TM(.)$, are close to each other for the base scenario S0, partial and complete replanning. However, the effect of delay disturbance becomes more clear when we address shipment-specific PIs.

Table 4
Performance Indicators (PIs) for complete vs partial replanning approaches under service delays (S1).

Replanning approach	Delay duration	PI	Shipments K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	Average
Partial	2 to 6 h	$FR(\%)$	8.7	6.09	3.73	3.48	3.26	0	4.35	3.86	4.35	0	3.78
		$CC(\%)$	0.17	0	0	0	0	0	0	0	0	0	0.02
		$MS(\%)$	0.48	0	0	0	0	0	0	0	0	0	0.05
	8 h	$FR(\%)$	8.7	6.09	3.73	3.48	3.26	0	4.35	3.86	4.35	0	3.78
		$CC(\%)$	0.17	0	0.57	0	0	0	0	0	0	0	0.07
		$MS(\%)$	0.48	0	0.62	0	0	0	0	0	0	0	0.11
	10 h	$FR(\%)$	8.7	6.09	3.73	3.48	3.26	0	4.35	3.86	4.35	0	3.78
		$CC(\%)$	2	0	0.57	0	0	0	0	0	0	0	0.26
		$MS(\%)$	0	0	0.62	0	0	0	0	0	0	0	0.06
	12 h	$FR(\%)$	8.7	5.22	3.73	3.48	3.26	0	4.35	3.86	4.35	0	3.7
		$CC(\%)$	2.46	0.79	0.57	0	0	0	0	0	0	0	0.38
		$MS(\%)$	0.46	0.68	0.62	0	0	0	0	0	0	0	0.18
Complete	2 h	$FR(\%)$	8.7	14.78	3.73	13.91	3.26	8.7	4.35	3.86	5.8	0.62	6.77
		$CC(\%)$	−0.83	0	0	18.73	0	−6.41	0	0	0	0	1.15
		$MS(\%)$	0.48	0	0	5.22	0	4.35	0	0	0	0	1.01
	4 h	$FR(\%)$	8.7	13.04	4.97	16.52	3.26	11.59	6.09	3.86	5.8	1.24	7.51
		$CC(\%)$	0.17	0	0	28.09	0	−8.54	−1.09	0	0	0	1.86
		$MS(\%)$	0.48	0	0	7.83	0	5.8	0.72	0	0	0	1.48
	6 h	$FR(\%)$	8.7	13.91	4.97	13.91	3.26	10.14	6.09	3.86	10.14	1.86	7.68
		$CC(\%)$	0.17	0	0	23.41	0	−6.94	−1.09	0	0	0	1.56
		$MS(\%)$	0.48	0	0	6.52	0	4.71	0.72	0	0	0	1.24
	8 h	$FR(\%)$	8.7	19.13	6.83	20.87	4.35	15.22	6.09	3.86	11.59	2.48	9.91
		$CC(\%)$	0.17	0	0.57	35.9	−0.1	−11.21	−1.09	0	0	0	2.42
		$MS(\%)$	0.48	0	0.62	10	0.95	7.61	0.72	0	0	0	2.04
	10 h	$FR(\%)$	8.7	22.61	8.07	26.96	4.35	21.01	6.09	3.86	11.59	1.24	11.45
		$CC(\%)$	2	0	0.57	46.82	−0.1	−14.95	−1.09	0	0	0	3.33
		$MS(\%)$	0	0	0.62	13.04	0.95	10.14	0.72	0	0	0	2.55
	12 h	$FR(\%)$	8.7	20.87	6.83	26.96	4.35	21.74	6.09	3.86	11.59	2.48	11.35
		$CC(\%)$	2.46	0.9	0.57	48.38	−0.1	−15.48	−1.09	0	0	0	3.56
		$MS(\%)$	0.46	0	0.62	13.48	0.95	10.51	0.72	0	0	0	2.67

Performance indicators of partial vs complete replanning under S1. Table 4 presents the effect of flows re-routed FR, average unit shipment cost change CC, and deviation of modal split MS per shipment based on the delay duration. The first column represents the replanning approach, the second column shows the duration of delay and the third column is associated with the evaluated PI index. Shipments are indicated as K1, K2, …, K10 in columns 4 to 13. The last column provides the average values over all shipments.

The outcome of the partial replanning for a delay duration from 2 to 6 h is the same, which is why they are shown together. It can be seen that the percent of flows re-routed, $FR(\%)$, remains the same for a delay duration from 2 h to 10 h in partial replanning. In particular, K6 and K10 are not affected from the delay disturbance under partial planning. On the other hand, unit cost change per shipment increases as the delay duration does. This can be regarded as marginal in the average, as mentioned in Table 3, although the cost change per shipment can be up to 2.46% when the delay duration increases to 12 h.

Transport mode changes become more visible when deviation in modal split $MS(\%)$ is examined per shipment. However, for partial replanning these changes are very limited. When we compare the differences in transport mode changes for each pair of delay duration (e.g., 8 h vs 10 h delay, 10 h vs 12 h delay etc.) for each disrupted leg in partial replanning, there is no evidence indicating a statistical difference and p-values of the paired t-test are always greater than 0.1.

However, similar conclusions cannot be drawn for the complete replanning case. We observe a p-value of less than 0.05 as the outcome of the paired t-test for delay pairs of (i) 2 to 6 h and 8 h, (ii) 2 to 6 h and 10 h, and (iii) 2 to 6 h and 12 h for complete replanning. This implies that for longer delays (e.g., more than 8 h) replanning results significantly deviate from the original plan in S0. Besides, there is statistical evidence that the difference of $MS(\%)$ between partial and complete replanning are significant for each delay duration (2 to 6 h, 8 h, 10 h and 12 h). Each case has a p-value of less than 0.05 as the outcome of the paired t-test. Note that the total cost values are the same for delay duration from 2 h to 6 h.

Concluding remarks. For a delay duration of 2 h to 6 h, it is more beneficial to consider partial replanning instead of complete replanning, because the costs are the same. In fact, complete replanning adds more uncertainty, since it requires more changes in the original plans. On the other hand, for delay duration of 12 h complete replanning provides significant cost savings when compared to the partial replanning. This implies that there is a trade-off between two planning approaches. Based on the outcomes of our proposed approach, we suggest using partial replanning for short delays and complete replanning for longer delays in the schedules. Note that a shipment can be split among different routes and not all flows of the shipment will be affected. Therefore,

Table 5
Summary of results for partial vs complete replanning under service cancellations (S2).

		S0	S2	
			Partial replanning	Complete replanning
	Total Cost	374360	559530.43	386582.61
	$TM(1)(\%)$	44.12	43.32	43.12
	$TM(2)(\%)$	38.97	38.71	38.97
	$TM(3)(\%)$	16.91	17.96	17.91
NR1	Total CPU (s)	62.76	2.76	51.98
	Model (M) CPU (s)	7.18	0.01	0.02
	Alg. 1 CPU (s)	50.30	2.25	51.61
	# of path calls	60	2.52	62.17
	# of paths added	37	1.61	37.70
NR2	Total CPU (s)	15.53	0.36	3.27
	Model (M) CPU (s)	7.24	0.01	0.01
	Alg. 1 CPU (s)	3.29	0.09	3.19
	# of path calls	70	2.13	69.57
	# of paths added	38	1.26	37.87

Table 6
Performance Indicators (PIs) for complete vs partial replanning approaches under service cancellations (S2).

Replanning approach	PI	Shipments										Average
		K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	
Partial	$FR(\%)$	8.7	4.35	3.73	3.48	3.26	0	4.35	3.86	4.35	0	3.61
	$CC(\%)$	8.83	2.29	1.72	6.24	5.63	0	2.04	1.09	9.64	0	3.75
	$MS(\%)$	3.69	1.51	1.86	1.74	3.01	0	1.29	3.86	1.96	0	1.89
Complete	$FR(\%)$	8.7	22.61	13.66	37.39	7.61	31.16	4.35	3.86	18.84	3.73	15.19
	$CC(\%)$	8.83	3.49	1.72	67.11	5.52	−20.82	2.04	1.09	9.64	0	7.86
	$MS(\%)$	3.69	0.68	1.86	18.7	3.96	14.13	1.29	3.86	1.96	0	5.01

it can be better to replan all routes of the affected shipments, in an *intermediate replanning* approach between partial and complete replanning.

5.3.2. Analysis of partial vs complete replanning under S2

Tables 5 and 6 present the results of the service cancellation disruption scenario S2. Service cancellations have more severe impacts on the network than service delays. Although the results imply that the total cost increases in average by 3.2% for complete replanning approach, this is still not statistically significant when compared to partial replanning. Therefore, it is more informative to consider transport mode changes as well as other PIs in the following.

Performance indicators of partial vs complete replanning under S2. We see that partial replanning does not deviate significantly from complete replanning in Table 5. The costs change, $CC(\%)$, of some shipments with complete replanning, in Table 6, could be negative for the complete replanning whereas for partial replanning $CC(\%)$ is always positive. This is interesting yet expected since partial replanning merely re-routes the flows that are affected and complete replanning provides more flexibility for changes in shipment flows.

Figs. 4–6 illustrate how shipment plans can be affected by partial versus complete replanning approaches. In Fig. 4, the base scenario S0 solution is represented. Shipments K2, K4 and K6 are selected under a cancellation disruption (scenario S2) that occurs for a scheduled service of SR12 shown as the railway service route from Hamburg to Rotterdam via Duisburg in Table B.9.

The flow values for each shipment are represented using a 3-tuple placed over the arcs connecting the terminals using the service routes given in B.9. Note that time aspect is not stated in these figures for the sake of simplicity. Flows using different scheduled services (starting at different time periods) of the same SR are consolidated in the representation.

We consider a service cancellation for the railway arcs connecting Hamburg to Duisburg and Duisburg to Rotterdam which are part of the SR12. This is indicated with a cross over these arcs in Figs. 5 and 6. Initially, there is a flow of 40 units of shipment K2 over these arcs for S0. The shipment flow of K2 is sent to roadway arcs containing 60 units, therefore, it is not affected by the disruption. After cancellation of SR12, 40 units flow of shipment K2 are re-routed.

In partial replanning approach, only the affected cargo is re-routed. This results in sending 40 units of extra flow for K2 over the roadway services and the remainder of the shipment plan does not change as illustrated in Fig. 5. On the other hand, the complete replanning approach offers the flexibility of rerouting all the shipment flows in case there is merit. This results in greater changes and thus more deviations for the shipment plan compared to the partial replanning approach.

We see that the modal split as well as the routes of shipments K4 and K6 have changed significantly in the case of complete replanning. At a first glance, the complete replanning approach can have more deviations as such. When we take a closer look in Fig. 6, it can be seen that the overall flow over the barge and truck services connecting Rotterdam to Hull does not change. Nonetheless, shipment flows of both K4 and K6 are severely affected. The total cost of shipment is the same for both the partial and the complete replanning approaches.

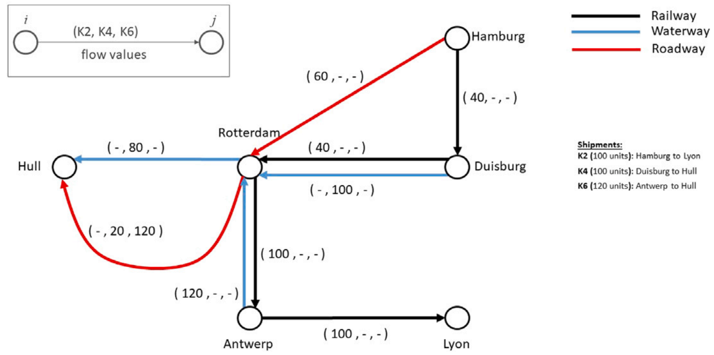

Fig. 4. Flow of shipments K2, K4 and K6 for S0.

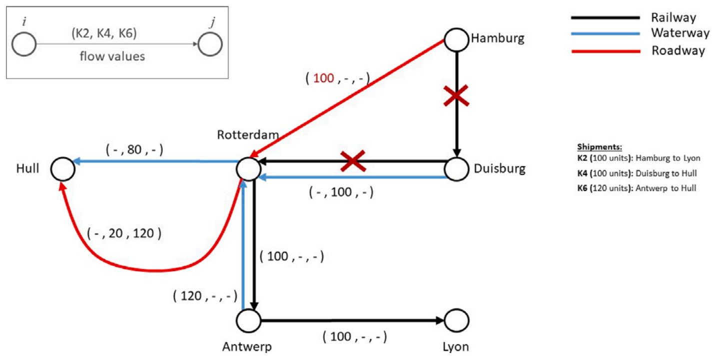

Fig. 5. Flow of shipments K2, K4 and K6 for S2 with partial replanning.

Concluding remark. Figs. 5 and 6 show a counter example for the case where increased flexibility does not always yields superior outcomes. Indeed, unnecessary replanning could propagate more distractions over different parts of the network in practice.

5.4. Managerial insights

For minor disruptions where only a few shipment flows are affected, using a partial replanning approach is recommended as it is a plausible alternative. Nevertheless, this phenomenon is highly connected with the severity of the disruption. In a network which is highly affected from a disruption, then partial replanning might yield inferior outcomes. In this case, the flexibility of complete replanning can be advantageous. The remaining time to first travel leg of a shipment might also have a significant impact for the re-routing decision and its extent. When there is sufficient time to organize loading/unloading, haulage and transfer of cargoes, then it can be more beneficial to include those cargoes for replanning. Therefore, an *intermediate approach* considers both the shipments affected from a disruption and the shipments that have room for re-routing in the analysis. Consequently, there is a trade-off between partial versus complete replanning, between fast response to disturbances versus flexibility in terms of replanning and between inferior solutions versus reduced transportation costs.

5.5. Observations on large instances

We have also performed an additional set of experiments to test the scalability of our methodology on a large instance. To that end, we increase the number of shipments to 100 shipments using the transportation network represented in Fig. 3. We have employed the same setting to generate the test instance as before. However, the demand of each shipment is selected from the interval $[5, 20]$ to make sure the feasibility of the instance. Here, we consider S2 as the disturbance scenario and our results are presented in Table 7.

The performance difference between NR1 and NR2 is more remarkable for the large instance. Now, the NR2 can be solved at least an order of magnitude faster than the NR1 in the average. This implies that the NR2 becomes more advantageous than the NR1 as the number of shipments increases. We observe that partial replanning can still be performed quickly bringing in scalability when compared with complete replanning. Indeed, partial replanning can be solved within 10.51 and 1.22 s using NR1 and NR2 representations in the average. However, these numbers are 408.1 and 18.7 s for the complete replanning using NR1 and NR2, respectively. Similar outcome is also observed for the number of times Algorithm 1 is called in partial and complete replanning.

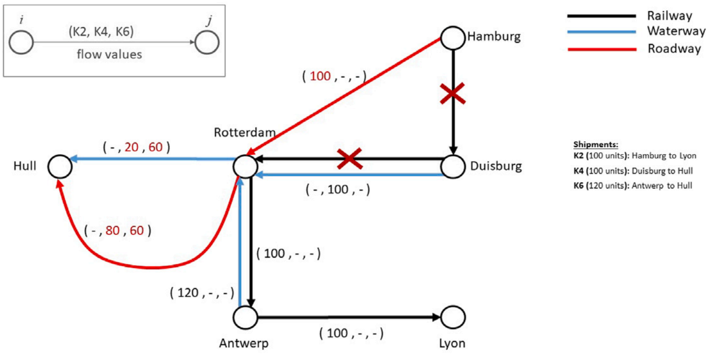

Fig. 6. Flow of shipments K2, K4 and K6 for S2 with complete replanning.

Table 7
Summary of results for partial vs complete replanning on larger test instance with 100 shipments under service cancellations (S2).

		S0	S2	
			Partial replanning	Complete replanning
	Total Cost	255684	266900.67	264282.89
	$TM(1)(\%)$	48.58	47.92	48.00
	$TM(2)(\%)$	44.80	44.27	44.47
	$TM(3)(\%)$	6.62	7.81	7.53
NR1	Total CPU (s)	435.83	10.51	408.10
	Model (M) CPU (s)	7.18	0.01	0.03
	Alg. 1 CPU (s)	422.22	9.73	406.56
	# of path calls	700	12.19	662.96
	# of paths added	311	7.22	306.00
NR2	Total CPU (s)	30.10	1.22	18.70
	Model (M) CPU (s)	7.35	0.00	0.01
	Alg. 1 CPU (s)	17.27	0.86	18.23
	# of path calls	600	13.17	600.00
	# of paths added	274	8.78	273.96

The number of columns added to model (M) is significantly higher for the complete replanning when compared with the partial replanning. On the other hand, although the total cost of using partial replanning is almost 1% more than the complete replanning, their difference is not statistically significant. Shortly, partial replanning arises to be a plausible alternative to quickly respond to the disturbances causing minimal change in the transportation plans even for large instances.

6. Conclusions

Persistent usage of long-distance road transportation have substantial negative environmental impacts. Intermodal transport can help reduce both operating costs and carbon footprints by combining waterway, railway and road transport modes (previously mentioned in Section 1). However, intermodal transport requires a strong coordination of scheduled services to harvest these benefits when disruptions occur. This calls for efficient algorithms to replan the shipments' distribution. In this paper, we considered a transportation replanning problem (TRP) that aims to find the minimum cost distribution plan of the shipments aftermath a disruption event and to enable a timely response by an LSP. We propose two network representations for an intermodal network and a tailored Column Generation (CG) algorithm as the resolution approach to tackle disruptions and delay management via partial and complete replanning. The proposed algorithm is easily adaptable to real-time replanning. Our proposed framework can be applied to any multimodal logistic network with available information on demand and disruption when replanning decisions are made centrally. In addition, based on our previously mentioned discussion, replanning for LSPs based on proposed approach will eventually result in reducing road transport. We have tested the model using a European intermodal logistic network on an extensive set of experiments mimicking real-life situations.

The intermodal network is represented by two network representations (NR1 and NR2). The first network representation employs a time–space network. It disjointly addresses time, travelling (scheduled network services) and physical terminals. The second network representation embeds the time aspect into both travelling and physical terminal connections. A path-flow based multi-commodity capacitated network flow formulation is introduced. A tailored CG algorithm is developed to solve the resulting problems for two network representations. The CG subproblems are resource constrained shortest path problems that are both NP-hard. We use a label-correcting algorithm to solve the pricing subproblems. The first network representation NR1 requires only one resource whilst

Table A.8
Origin and destination terminals, and demand quantity of shipments.

Shipment	Origin	Destination	Units
K1	Hull	Mannheim	120
K2	Hamburg	Lyon	100
K3	Mannheim	Hamburg	140
K4	Duisburg	Hull	100
K5	Rotterdam	Prague	160
K6	Antwerp	Hull	120
K7	Prague	Hull	100
K8	Mannheim	Rotterdam	180
K9	Lyon	Duisburg	120
K10	Rotterdam	Antwerp	140

the second network representation NR2 has two resources with additional arrival and departure time restrictions. The suggested CG algorithm yields promising results for both network representations where the latter provides significant savings and shows its scalability for the problem. Overall replanning takes less than a minute of time which makes the proposed approach suitable for real-time replanning.

Two replanning approaches, partial vs complete, are compared and analyzed on service delay and service cancellation disturbances. In partial replanning, original plan is inherited except for the shipment flows that are directly affected from a disturbance. In complete replanning, original plan can be changed for every flow regardless it is affected from a disturbance or not. Although complete replanning is more flexible than the partial replanning approach, we have exemplified the use of partial replanning can be as beneficial as a complete replanning in some cases. We show that the odds are in favor of partial replanning when the disruption event affects only a few shipment flows.

Decisions made without taking the scope of a disturbance into account can be injudicious. A drawback of a complete replanning is that the resulting change of shipment flows is usually bigger than in the case of partial replanning. Complete replanning approach for minor disruptions might propagate the disturbance further throughout the entire network and brings in additional risks of rearrangements at different terminals such as transfers and scheduled services. The other element is the allowance time for organizing a re-routing of a flow aftermath a disruption. When there is sufficient time to handle additional loading/unloading, haulage and transfer of a shipment, it is possible to include those cargo items for rerouting in replanning activities. Intermediate replanning, which re-routes both affected and unaffected flows (or split flows) by disruption provides a plausible option under these circumstances. This would enable to partially benefit from the advantage of a complete replanning for cost minimization and to keep unnecessary re-routing of flows at minimum as in partial replanning.

This study proposes a scalable algorithmic approach for real-time replanning after disturbances occur. Our methodology can be extended to handle other disturbances, such as changes in capacity, demand and delivery time restrictions and arrival of new cargo. Current methodology is also limited to customer requirements concerning delivery times and the number of transshipment. Different types of cargoes with different priorities such as fragile, expensive products with small volume, or products requiring cold chain transportation can be incorporated into our methodology as further research. Future research can incorporate stochasticity in replanning to produce robust plans that are viable for a potential future disruption. And, last but not least, it would be worthwhile to examine the impact of road congestion on replanning activities.

CRediT authorship contribution statement

M. Hakan Akyüz: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Data curation, Validation, Visualization. **Rommert Dekker:** Conceptualization, Methodology. **Shadi Sharif Azadeh:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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Appendix A. Shipment details

See Table A.8.

Appendix B. Service routes details

See Table B.9.

Table B.9
Description of the service routes (SRs).

Name	Port-of-calls (duration)	Departure	Capacity	Transport mode
SR1–2	Hull $\xrightarrow{(15)}$ Rotterdam	$\{1, 25\}$	80	Waterway
SR3–4	Rotterdam $\xrightarrow{(9)}$ Duisburg	$\{1, 7, 13, \dots, 61\}$	80	Waterway
SR5–6	Rotterdam $\xrightarrow{(8)}$ Antwerp	$\{1, 7, 13, \dots, 61\}$	80	Waterway
SR7–8	Rotterdam $\xrightarrow{(9)}$ Duisburg $\xrightarrow{(21)}$ Mannheim	$\{1, 25\}$	80	Waterway
SR9–10	Rotterdam $\xrightarrow{(14)}$ Prague	$\{13, 37, 49\}$	40	Railway
SR11–12	Rotterdam $\xrightarrow{(4)}$ Duisburg $\xrightarrow{(5)}$ Hamburg	$\{13, 37\}$	40	Railway
SR13–14	Rotterdam $\xrightarrow{(7)}$ Antwerp $\xrightarrow{(21)}$ Lyon	$\{1, 13, 25, 37, 49, 61\}$	40	Railway
SR15–16	Rotterdam $\xrightarrow{(4)}$ Duisburg $\xrightarrow{(10)}$ Mannheim	$\{1, 7, 13, \dots, 61\}$	40	Railway
SR17–18	Hull $\xrightarrow{(11)}$ Rotterdam (11)	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR19–20	Rotterdam $\xrightarrow{(9)}$ Mannheim	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR21–22	Rotterdam $\xrightarrow{(2)}$ Duisburg	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR23–24	Duisburg $\xrightarrow{(10)}$ Prague	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR25–26	Hamburg $\xrightarrow{(9)}$ Prague	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR27–28	Duisburg $\xrightarrow{(3)}$ Hamburg	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR29–30	Rotterdam $\xrightarrow{(4)}$ Hamburg	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR31–32	Rotterdam $\xrightarrow{(13)}$ Lyon	$\{1, 3, 5, \dots, 61\}$	–	Roadway
SR33–34	Duisburg $\xrightarrow{(6)}$ Mannheim	$\{1, 3, 5, \dots, 61\}$	–	Roadway

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