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Intermodal Logistic Systems Under Multiple Disruptions

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ABSTRACT

Intermodal transport has become globally acknowledged thanks to its numerous advantages such as lower transportation costs, economies of scale and carbon emission reduction. Yet utilization of multiple transport modes requires greater coordination and communication. Intermodal transport frequently faces disruptions in operations such as delays and service cancellations, which in turn may require replanning of shipment plans. Akyüz et al. (2022) propose a Column Generation (CG) algorithm as a resolution to the Transportation Replanning Problem (TSP), along with different replanning approaches. In this paper, we extend the work of Akyüz et al. and test the proposed approaches on different disruption scenarios using a European intermodal transport network. We use our results to draw conclusions on the effectiveness of the methods.

Keywords: Replanning intermodal transportation, Multi-commodity network flow, Column generation, Disruptions.

Contents

1 Introduction

Intermodal transport has become a dominant option in supply chain and logistics globally as it offers many benefits such as lower transportation costs, economies of scale and carbon emission reduction, to name a few. It combines roadway transport with other modes of transport and offers the possibility to lower the costs. This does not come without setbacks, however, as it requires a good logistic coordination. Intermodal transport frequently faces obstacles that arise from irregularities in operations such as arrival of new shipment orders, fluctuations in shipment quantities, delays and service cancellations within the network (Akyüz et al., 2022). These irregularities, referred to as disturbances in this paper, may render transportation plans invalid in practice and require replanning of the shipments.

Our main research question then becomes ***"How can we efficiently replan the shipment plans after a disturbance occurs under different scenarios?"***. We build on the study of Akyüz et al. (2022), which formulates the problem as a path based multi-commodity flow formulation and proposes a tailored Column Generation(CG) algorithm. The algorithm utilizes two different replanning approaches in order to generate a new shipment plan. Partial replanning approach reroutes only the flows affected from the disturbances, and complete replanning approach reroutes every shipment regardless of their status in regards with the disturbances.

The original paper of Akyüz et al. (2022) considers two types of disturbances: service delays and service cancellations. The analysis is based on occurrence of a single disturbance throughout the planning horizon. In this paper, we formulate our sub-question as ***"How is the status of the service network affected when multiple disturbances occur, and does the effectiveness of the proposed replanning approaches change under different scenarios?"***. We extend the work of the original paper and construct 3 additional scenarios. In the first scenario, we assume multiple cancellations occur throughout the planning horizon, in the second scenario multiple delays, and in the final scenario both cancellations and delays. As a bonus, we test the approaches on multiple cancellations scenario with additional shipments. We use the results to analyze how complete and partial replanning behave under different scenarios, and how the trade-off between them is affected.

Our findings indicate that the two replanning approaches may display different patterns under different disturbance scenarios and the dominance is mainly case dependent. Although complete replanning offers lower transportation costs in each scenario, in most cases the differences are not statistically significant, particularly in delay scenarios (both single and multiple). Besides, complete replanning makes an excessive amount of modifications to the shipment plan and is 2 to 3 times slower than partial replanning. We conclude that partial replanning can still be applied in most cases although it lacks the flexibility of complete replanning and may generate inferior results.

As intermodal transportation continues to be globally acknowledged, the topic becomes of great relevance both theoretically and practically. It is crucial for researchers and Logistic Service Providers, and many studies have been devoted to this topic such as Bock (2010) which focuses on fleet management, Demir et al. (2016) which studies an offline intermodal service network problem under demand and travel time uncertainties, and van Riessen et al. (2015) which proposes a complete enumeration scheme to solve a similar problem. The original paper of Akyüz et al. (2022) and therefore this paper focus on replanning the flow of shipments in case of disturbances that is adaptable to the real-time cases and larger networks. Our research results mainly aid companies such as P&O Ferrymasters or Samskip which operate a European intermodal network (Akyüz et al., 2022).

The rest of this paper is organized as follows. Section 2 gives a detailed description of the replanning problem. Section 3 summarizes similar studies to our research. Next, the notation and the constrained model is introduced in Section 4. Finally, we give a detailed analysis of our experiments in Section 5 and conclude our research in Section 6.

2 Literature Overview

We can categorize the existing studies into two main groups according to the modalities used to transfer shipments: single and intermodal logistic transport. The single modal transport typically deals with replanning the transportation units, while the intermodal transport replans the whole shipment. Here, we focus on intermodal transport papers and compare the approach of Akyüz et al. (2022) to the relevant literature.

Atasoy et al. (2022) incorporates service flexibility in synchromodal transport framework by use of flexible services that provide dynamic optimization for adapting the planning in case of disruptions. Considering computational complexity, an Adaptive Large Neighborhood Search heuristic is designed to solve the problem on a small scale logistic network.

Behdani et al. (2016) develop an MILP formulation to construct service schedules over a predefined planning period for freight transportation. In contrast to Akyüz et al. (2022), only a single origin-destination pair is used and possibility of disruption events at the destination are not considered.

Bock (2010) offers a real-time transportation planning model and heuristic approaches to cope with dynamic disturbances occurring mainly on road transport such as vehicle breakdowns, road blockages, traffic congestion as well as new transportation orders. The original paper is also in line with the work of Bock (2010) if their vehicle fleet module is replaced by container routes and is adapted to real-time disturbances in an intermodal system. The original paper focuses on replanning the flow of shipments instead of fleet management.

Ahmady and Yeghaneh (2022) develop a multi-objective optimization approach for disturbance response preparation in intermodal freight road–rail networks. The aim of the optimization model is to find a balance between transport costs and the freight transport system's operation efficiency determined by the portion of consumer demand delivered on time. An enhanced ε-constraint approach and a heuristic routing algorithm are suggested to solve the problem.

Demir et al. (2016) study an offline intermodal service network design problem to construct routes for the shipments and select scheduled services under demand and travel time uncertainties taking environmental impacts into account The resulting problem is a tactical level problem and solved via a sample average approximation method.

Negenborn et al. (2022) investigate a collaborative variant of the berth allocation recovery problem and propose a mixed-integer programming model to (re)optimize the initial allocation plan in case of disruptions. A Squeaky Wheel Optimization metaheuristic is developed to find near-optimal solutions for large-scale instances. If we include railway and roadway transportation modes, the problem setting of Negenborn et al. (2022) is very similar to that of Akyüz et al. (2022).

Hrusovsky et al. (2021) offer an integrated simulation-optimization based decision support tool for disruption management. The plannings 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. The proposed model and network representations of Akyüz et al. (2022) present a scalable alternative for their mathematical model to cope with disruptions.

Huang et al. (2011) propose a decision method for dealing with disruption events in intermodal freight transport. In addition, their resolution includes a forecasting process which decides whether a rearrangement is needed. If so, a network-based optimization model for intermodal freight transport disruption management is solved using an improved depth-first search strategy, which achieves recovery strategies quickly.

van Riessen et al. (2015) focus on the operational planning problem concerning the allocation of classes of containers to inland services in a predefined service schedule under disruptions such as early/late service departures or cancellations of these services. The proposed approach of Akyüz et al. (2022) is more general in the sense that it keeps the definition of delays broad, which involves an early or late departure. In addition, Akyüz et al. (2022) take into account not only the inland but also water services. This requires developing scalable algorithms tailored for larger networks. For this, Akyüz et al. (2022) suggest an integrated Column Generation (CG) approach for replanning instead of an independent path generation approach as in van Riessen et al. (2015). We observe that shipment replans can be found very quickly by the CG approach, which brings in scalability that is not present for most of the studies mentioned.

3 Problem Description

A customer is defined as the owner of a shipment, also referred to as cargo or commodity, that is to be delivered from an origin terminal to its destination (Akyüz et al., 2022). Each customer has certain demand and desires it to be delivered in a given time window. Customers can select the price and quality of the service, but the rest of the transportation is organized by the LSP, specifically the route/shipment plan and transport modes used. We set the length of the planning horizon as one week.

We distinguish two important definitions in transportation services. A service route (SR) consists of a given sequence of visits to terminals using a single transport mode while a scheduled service, or shortly a service, is actualization of a SR that starts its journey at a specific time. Thus, a service route has multiple scheduled services, each corresponding to a different starting time. We consider 3 types of transportation modes: water, rail and road transport. Furthermore, we define disruptions as irregularities in operation, arising from delays or cancellations on services, traffic congestion, etc., which in turn require replanning of the routes for the shipments. Short term disruptions with effects that span less than 24 hours are considered as minor disruptions and as major disruptions otherwise (Qi, 2015). In this study, minor disruptions are referred as disturbances. We look at two types of disturbances: scheduled service delays and cancellations. Additionally, only disturbances that occur in waterway or railway are taken into consideration since roadway services can be easily compensated, unlike waterway and railway SRs, in case of a disruption where often there exists an alternative roadway to use (Akyüz et al., 2022).

Given weekly demand of shipments and scheduled services, we solve the Transportation Replanning Problem (TRP) in order to find an alternative shipment plan aftermath a disturbance with the minimum total transportation cost subject to capacity constraints of the scheduled services and time restrictions by the customers. The framework is a disruption management tool for intermodal logistic system that is adaptable to the real-time cases and works offline in the case of disturbances (Akyüz et al., 2022).

3.1 Assumptions

We keep our assumptions the same as that of Akyüz et al. (2022), and formulate TRP based on the following assumptions:

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 has the full information about the disruptions as soon as it occurs based on the time of occurrence, duration and the affected connections.

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 1 and 2 imply the demand and the scheduled services are fixed and known. Assumption 3 implies late delivery is not accepted, and shipments that are not delivered on time are considered a loss. Assumption A4 restricts the number of maximum transshipment per shipment since each transshipment requires operation handling and creates additional risk of distortion in the plan. Assumption 5 ensures that the LSP complete and immediate information on the disturbances, and therefore can react without uncertainty. Assumption 6 gives the LSP the freedom to select the best transportation option possible in terms of costs, time and emission savings.

3.2 Network Representation

Akyüz et al. (2022) propose two network representations (NR) to model the intermodal service network. The first network representation (NR1) is based on a time-space network following a discretization strategy over time. The second network representation (NR2) addresses time implicitly, creating a dummy node for each scheduled service of a service route. Both network structures require the solution of the NP-hard problem resource constrained shortest paths (Akyüz et al., 2022).

In this study, we focus only on the first network representation. For illustrative purposes, we add a drawing of the network in the appendix Figure 2. Addressing time explicitly, NR1 makes the implementation straightforward. A separate node is created for each terminal to represent different points in time, and the arcs connecting the nodes keep track of starting and ending times of the journey.

4 Methodology

4.1 Notation

We borrow the notation of the original paper. Table 1 shows all the variables and parameters used together with their description.

Table 1: Notation (Akyüz et al., 2022)

Indices	
a	An arc $a = (i, j)$ connecting node i to node j of the service network
d^k	Destination node of shipment k
g	Transport mode representing waterway, railway or roadway
i	Node associated with the service network
j	Node associated with the service network
k	Shipment
l	Label
o^k	Origin node of shipment k
p	Path
t	Time period
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
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_f^k	The cost of loading/unloading a unit of shipment k at a terminal
c_g^k	Travelling cost rate per transportation mode g for shipment k
c_p^k	The total cost associated with path p for a unit of shipment k
c_{ij}^k	The cost of sending a unit of shipment k over the arc (i, j) from node i to node j
c_w^k	The cost of waiting (w) for a time period per unit of shipment k at a terminal
δ	Duration of delay disruption
e_{ij}	Arrival time at node j when arc (i, j) is used
q^k	Customer demand (in TEUs[1]) for shipment k
t_{ij}	The travel time over the arc (i, j) from node i to node j
t_p^k	The travel time over the path $p \in \mathcal{P}^k$ for shipment k

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Table 1: Notation (Akyüz et al., 2022) (Continued)

A	The number of arcs in the graph $\mathcal{G} \equiv \lvert\mathcal{A}\rvert$
C_i^l	Cost weight of label ℓ for node i
H	The number of physical terminals in the transportation network
K	The number of customer shipments $\equiv \lvert\mathcal{K}\rvert$
F_i^l	Transshipment weight of label ℓ for node i
N	The number of nodes in the graph $\mathcal{G} \equiv \lvert\mathcal{N}\rvert$
S	The number of scheduled services
T	The number of time periods in the planning horizon $\equiv \lvert\mathcal{T}\rvert$
T_i^l	Transit time weight of label ℓ for node i
T_{max}^k	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_p^k	Amount of flow of shipment k over path p

4.2 Transportation Replanning Problem (TSP)

We first introduce the model to find an optimal shipment plan under no disturbance setting. For each commodity k, we generate a set of feasible paths, $\mathcal{P}^k$, that adhere to the restrictions of the network as well as the desires of the customers such as delivery time requests, service route capacities and maximum number of transshipments allowed. These restrictions can be considered as resources and can be embedded within path generation procedure (Akyüz et al., 2022).

The amount of flow for commodity k over path p is indicated by the continuous decision variable λ_p^k with the associated total cost c_p^k. The total cost includes the transportation (c_{ij}^k), transshipment (c_f^k) and waiting (c_w^k) costs on path p. We then introduce the binary parameter y_{pa} taking a value of one when arc a is part of the path p and zero otherwise. We denote the total flow capacity of an arc $a = (i, j)$ with u_a. To ensure feasibility of the solution, we create a dummy arc for each commodity k from its origin $i \in \mathcal{O}$ to its destination terminal. The dummy decision variable β^k shows the amount of flow over the dummy arc for each commodity k with the associated penalty term c^k.

Then the problem is modelled by a path-flow based multi-commodity capacitated network flow model (M):

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

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

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

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

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

The objective function minimizes the total cost of transportation flowing through all the paths as well as the dummy arcs. The first set of constraints makes sure that the demands of the customers are satisfied. The second set of constraints ensure that the capacity limit of arc $a=(i,j)$ is not exceeded. Note that the delivery time and maximum number of transshipment restrictions are already taken care of while generating the paths. Finally, third and fourth constraints impose the non-negativity restrictions of variables.

(M) is a generic model and can be used to generate optimal shipment plans for any path-flow based network adhering to the above mentioned setting. Hence, as long as the network status is up-to-date, the Transportation Replanning Problem (TSP) becomes solving (M) in a rolling horizon fashion whenever a disturbance occurs in the network to provide recovery plans. Thanks to the capability of modern technology, status of the scheduled services such as capacity, arrival and departure times changes are regularly updated and known (Akyüz et al., 2022). We name the replanning approach by solving (M) from scratch as complete replanning.

Akyüz et al.(2022) propose a tailored Column Generation (CG) algorithm to solve (M) that generates paths with lower objective value than the previous solution. For the initial solution, we carry all the flow through the dummy arcs from origin nodes to destination nodes with high penalty values. Then, the new paths are added to the constraint matrix as columns, and the algorithm continues to generate new columns until there is no cost reduction possible for a commodity k.

4.3 Resource Constrained Shortest Path Problem (RCSPP)

Finding the path having the most reduced cost value can be achieved by solving the shortest path problem with reduced cost values for a commodity k.Thus, the resulting pricing subproblem becomes a resource constrained shortest path problem (RCSPP) under delivery time and/or transshipment constraints (Akyüz et al., 2022). Label correcting algorithm is used on the problem to find the shortest, or cheapest in our context, path for commodity k. The pseudocode of the algorithm is shown in Algorithm 1 in the appendix.

We make use of 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."(Akyüz et al., 2022) and the fact that the roadway arcs are assumed to have no capacity restrictions at all. We name the replanning approach by solving RCSPP per affected shipment flow as partial replanning. Partial replanning is evidently faster than complete replanning yet may produce inferior solutions in case many shipments are affected by a disturbance.

5 Results

In this section, we first introduce the setting under which the experimentation are carried as well as the data used. Then, we replicate the results of Akyüz et al. (2022) and summarize the main findings. Finally, we present our results of extension scenarios and provide a detailed analysis of the results.

We use Julia programming language v1.7.0 combined with JuMP package and Gurobi optimizer v9.1.2. The results are generated on a PC with Dual Intel Core i5, 2.7 GHz Processors and 8 GB RAM operating within 64-bit MacOS Catalina v10.15.6 environment.

5.1 Data

We make direct use of the data gathered from the original paper Akyüz et al. (2022) for replication and extension purposes. The data includes all cost, timing and demand values associated with the network as well as information on scheduled services.

We use a European intermodal transport network consisting of terminals connected to each other via railway, waterway and/or roadway services. The service network is constructed using the intermodal network of P&O[2] as presented in Figure 1. Service routes are assumed to be symmetric such that if SR1 represents water transportation from "Hull" to "Rotterdam", SR2 represents water transportation from "Rotterdam" to "Hull".

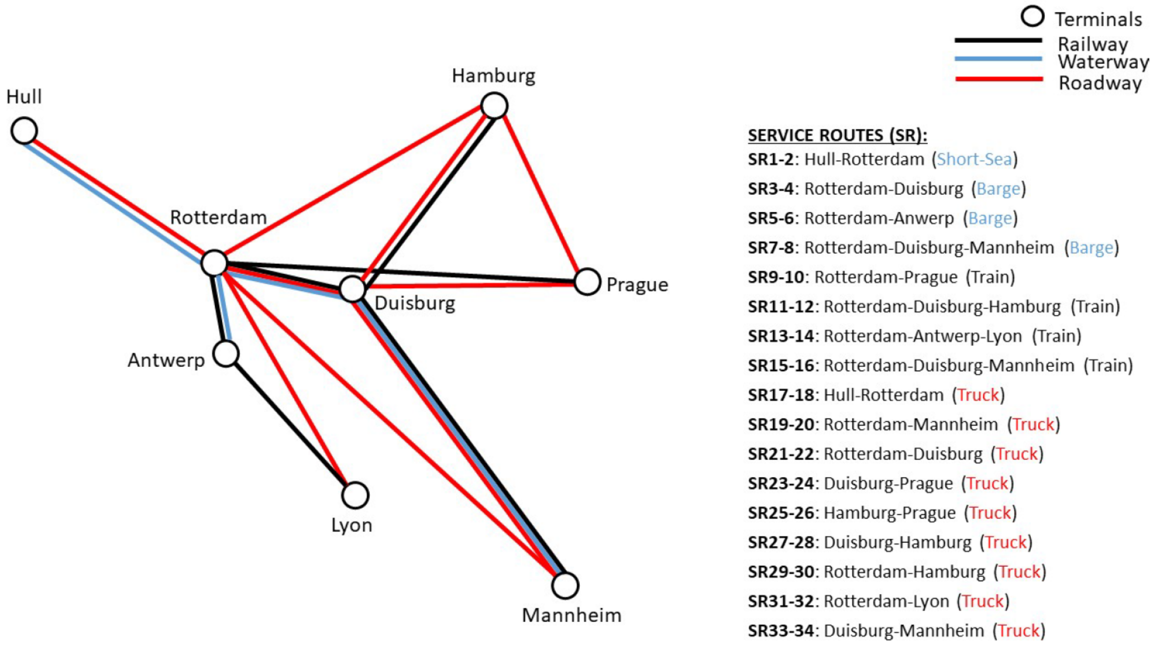

Figure 1: Intermodal service network (Akyüz et al., 2022).

There are 8 physical terminals, 34 service routes, 96 scheduled services for railway and waterway service routes, and 558 scheduled services for roadway service routes. 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 (Akyüz et al., 2022). The planning horizon is equal to $T = 84$ time periods, where each time period is assumed to have two hours of length (one

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

week is $7 \cdot 24 = 168$ hours). The dummy arcs from origin to destination terminal for every shipment k are assumed to be roadway(or truck) connections. A summary of the SRs is given in Table 15 in the appendix. 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 (Akyüz et al., 2022). Note that the departures are given in time units and not hours.

Cost parameters associated with the arcs on the network are borrowed from the work of van Riessen et al. (2015) and are calculated based on Table 2.

Table 2: Unit transportation costs by van Riessen et al. (2015)

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)

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 of waiting arcs are assumed to be at a symbolic rate of $c_w^k = 1$ per time unit for every shipment. This avoids unnecessary waiting of the shipments in the terminals which may result in undesirable paths to be constructed (Akyüz et al., 2022). The penalty cost c^k associated with the flow β^k is set to 10^6. The arc capacities of waterway, railway and roadway are 80, 40 and unbounded, respectively. The average speed per transport mode is set as 12, 30, and 60 kilometers per hour for waterway, railway and roadway services, respectively, and used in the calculations of c_{ij}^k values. These values are set following the suggestions from AbOvo[3]. Travel time between any pair of terminals are computed using an online calculator[4] designed 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 travel times for each service route.

The origin and destination terminals of the shipments are randomly chosen among the pairs of terminals. 10 commodities are randomly generated for which the demand size is selected from a given interval [100, 200] as a multiple of ten, see Table 16 in the appendix for the summary of the generated commodities. The shipments are assumed to be available at the first time period and each has a delivery time restriction of 140 hours or 70 time units.

We solve (M) on the above-mentioned settings without any disturbances in order to construct the base scenario (S0). Later, after the occurrence of a disturbance, the status of the network and the performance of the two replanning approaches, complete and partial replanning, are compared to the base scenario. We compare the objective values, which may deviate from the base scenario, as well as three Performance Indicators (PIs) that we define in the following paragraphs.

The overall performance of the intermodal network is measured using the total cost of the shipment plan, using the objective function value, and the percentage of flows over different transport modes. The percentage of flows is calculated using the following formula:

$$TM(g) = 100 \times \frac{\sum_{k \in \mathcal{K}} \sum_{p \in \mathcal{P}^k} \sum_{a \in \mathcal{A}} y_{pa}^g \lambda_p^k}{\sum_{k \in \mathcal{K}} q^k} \tag{1}$$

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[3] (https://ab-ovo.com/) is a Dutch consulting company providing software solutions for supply chain and logistics companies.

[4] https://rotterdam.navigate-connections.com/voyages

where TM(g) stands for the percentage of flow carried over transport mode $g \in \{1,2,3\}$ with $g = 1$ for waterway, $g = 2$ for railway and $g = 3$ for roadway transportation. y_{pa}^{g} takes value 1 when arc a is part of path p for transport mode g and 0 otherwise.

We consider the three shipment specific PIs to get more insight on how disturbances affect the network. The PIs show the relative change of plans with respect to the base scenario S0 of Akyüz et al. (2022). The first PI is the percent of flows re-routed (FR) compared to S0. The paths used for commodity k in disturbance scenarios are compared with that of the base scenario. Any flow using a different path than the base scenario is considered re-routed. The sum of all re-routed flows of commodity k is divided by the total demand for k to get the percentage change, FR.

The second PI is the average unit shipment Cost Change (CC) compared to S0. The average unit shipment cost $ASC^{S_i(k)}$ for shipment k is calculated as $ASC^{S_i(k)} = \frac{\sum_{p\in\mathcal{P}^k} c_p^k \lambda_p^k}{q^k}$, where S_i represents a specific scenario, e.g. base scenario S0 or disturbance scenario S. Then, CC of disruption scenario S for commodity k is determined as $CC^k = \frac{100\times(ASC^{S(k)} - ASC^{S0(k)})}{ASC^{S0(k)}}$. CC^k can be both positive or negative depending on the overall structure of flows and disturbances. When a bottleneck arc has some extra capacity after a disruption happens in some parts of the network, it may be filled up by another shipment k that is unaffected by the disruption, therefore, leading to lower unit shipment cost for shipment k (Akyüz et al., 2022). Yet, we expect it to increase in general.

The final PI is the deviation of Modal Split (MS) per commodity between the base scenario S0 and a disruption scenario. We first calculate $TM(g)$ values for S0 and the disturbance scenario S, $TM(g)^{S0}$ and $TM(g)^{S}$, for each transport mode $g \in \{1,2,3\}$. We define MSC^k as the modal split change per shipment k and calculate it as $MSC^k = [TM(1)^{S0} - TM(1)^{S}, TM(2)^{S0} - TM(2)^{S}, TM(3)^{S0} - TM(3)^{S}]$. Since elements of MSC^k can be both positive and negative, we use standard deviation to represent the modal split change after a disruption, $MS^k = std(MSC^k)$ for commodity k.

5.2 Replication

Akyüz et al. (2022) use the work of van Riessen et al. (2015) as benchmark, which follows a complete enumeration scheme to solve a similar problem to TRP. As we already know this that approach yields the same values as the base scenario of Akyüz et al. (2022), we omit it from our analysis. We focus on the base scenario, and the two disturbance scenarios S1 and S2 mentioned in the paper of Akyüz et al. (2022). S1 considers the occurrence of a single service delay while S2 considers a single service cancellation. We present our replication results in Sections 5.2.1 and 5.2.2, and summarize the main findings of the original paper.

5.2.1 Partial vs Complete Replanning Under S1

In scenario S1, a scheduled service is assumed to have a delay for a certain duration between two scheduled services of the same service route. We examine delay durations of $\delta \in \{2,4,6,8,10,12\}$ hours. This is repeated for every scheduled service of each service route, and we report the average obtained over all scheduled services of the service routes for one particular delay duration (e.g. 8 hours). It is assumed that the corresponding service would be cancelled if it goes beyond 12 hours of delay. The results of partial and complete replanning, including the objective values, CPU times and TM values, are shown in Table 3 together with the PI measure for each commodity in Table 4.

Table 3: Results summary for partial vs complete replanning under service delays (S1)

	S0	S1							
		Partial Replanning				Complete Replanning			
Duration		2 to 6 hrs	8 hrs	10 hrs	12 hrs	2 to 6 hrs	8 hrs	10 hrs	12 hrs
Total Cost	374360	374405.22	374606.96	375083.48	462084.35	374405.22	374565.22	375041.74	375459.13
NR1 CPU (s)	94	22.58	24.85	27.55	23.80	86.93	86.28	86.82	86.87
TM(1)(%)	44.12	43.13	44.13	44.13	44.23	44.12	44.03	44.03	44.05
TM(2)(%)	38.97	38.89	38.83	38.76	38.60	39.03	39.07	39.01	38.97
TM(3)(%)	16.91	16.98	17.04	17.10	17.17	16.85	16.90	16.96	16.98

The first observation to note is that the total transportation cost for partial replanning is always greater than or equal to that of complete replanning. On the other hand, it is also approximately 4 times faster compared to complete replanning as it only reroutes the disrupted flows. Partial replanning manages to produce similar total costs to the base scenario up until delay duration of 10 hours with a large peak for delay duration of 12 hours while complete replanning does not seem to be critically affected by the disturbances. A t-test of 10% significance level for each delay duration indicates that the total cost values for partial and complete replanning are not significantly different. Hence, the two replanning approaches yield similar outputs in terms of objective function value. Next, we examine the commodity specific PI measures.

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

Replanning Approach	Delay Duration	PI	Shipments										Average
			K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	
Partial	2 to 6 hrs	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 hrs	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 hrs	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 hrs	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 hrs	FR(%)	8.7	10.87	3.73	13.91	3.26	8.7	4.35	3.86	5.8	0.62	6.38
		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 hrs	FR(%)	8.7	9.13	4.97	16.52	3.26	11.59	6.09	3.86	5.8	1.24	7.12
		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 hrs	FR(%)	8.7	10	4.97	13.91	3.26	10.14	6.09	3.86	10.14	1.86	7.29
		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 hrs	FR(%)	8.7	14.35	6.83	20.87	4.35	15.22	6.09	3.86	11.59	2.48	9.43
		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 hrs	FR(%)	8.7	17.83	8.07	28.7	4.35	22.46	6.09	3.86	13.05	1.24	11.44
		CC(%)	2	0	0.57	49.94	-0.1	-16.02	-1.09	0	0	0	3.53
		MS(%)	0	0	0.62	13.91	0.95	10.87	0.72	0	0	0	2.71
	12 hrs	FR(%)	8.7	16.09	6.83	24.35	4.35	19.57	6.09	3.86	11.59	1.86	10.33
		CC(%)	2.46	0.9	0.57	43.7	-0.1	-13.88	-1.09	0	0	0	3.26
		MS(%)	0.46	0	0.62	12.17	0.95	9.42	0.72	0	0	0	2.43

Table 4 presents the flows rerouted FR, average unit shipment cost change CC, and deviation of modal split MS per commodity for each delay duration. For partial planning, $FR(\%)$ values remain the same except for 12 hours delay while $CC(\%)$ and $MS(\%)$ values tend to increase as the duration of the delay increases. Yet these increases are not significant as concluded by a t-test of 10% significance level. However, we cannot draw similar conclusions for complete replanning. For delay durations of longer than 8 hours, replanning results significantly deviate from the original plan in S0. Plus, the difference of $MS(\%)$ between partial and complete replanning are statistically different for each delay duration at 5% significance level.

We conclude that partial replanning is advantageous up to 10 hours delay as it produces similar total cost while being approximately 4 times faster. Besides, complete replanning brings in extra uncertainty since it requires more changes in the original plans (Akyüz et al., 2022). On the other hand, we see a clearer trade-off between cost and speed for 12 hours delay.

5.2.2 Partial vs Complete Replanning Under S2

Similar to S1, in scenario S2, each scheduled service is assumed to be cancelled one at a time, and the results are averaged over all cancelled scheduled services. The objective values, CPU times and TM values are presented in Table 5, and the PI measures for each commodity are shown in Table 6. Note that the service cancellations have more severe impacts on the network than service delays. They constitute the worst case bound on the disturbance outcome when compared with the delay disturbance of the same service (Akyüz et al., 2022).

Table 5: Results summary for partial vs complete replanning under service cancellations (S2)

	S0	S2	
		Partial Replanning	Complete Replanning
Total Cost	374360	559530.43	386582.61
NR1 CPU (s)	94	32.12	79.55
TM(1)(%)	44.12	43.36	43.12
TM(2)(%)	38.97	38.57	38.97
TM(3)(%)	16.91	18.07	17.91

Although the total cost value difference between partial and complete replanning approaches now becomes more visible, the difference is still not significant. $CC(\%)$ and $MS(\%)$ values also show similar statistics with the exceptions of commodity K4 and K6. We only see significant changes between the two replanning approaches for the flow rerouted $FR(\%)$ measures.

Table 6: Performance Indicators (PIs) for partial vs complete replanning 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	39.13	7.61	32.61	4.35	3.86	18.84	3.73	15.51
	CC(%)	8.83	3.49	1.72	70.23	5.52	-21.89	2.04	1.09	9.64	0	8.07
	MS(%)	3.69	0.68	1.86	19.57	3.96	14.86	1.29	3.86	1.96	0	5.17

5.3 Extensions

After replicating the results of the original paper, we analyze the effects of multiple disturbances under 3 different scenarios. In the first scenario (S3) we assume multiple service cancellations occur throughout the planning horizon, in the second scenario (S4) multiple service delays (of 6 hours), and in the final scenario (S5) both cancellations and delays. The total number of disturbances that occur during the planning horizon range from 2 to 3, where the time between two consecutive disturbances varies between 0–48 hours as a multiple of 24 hours. The rest of the settings stay the same as in the original paper. We repeat this for every scheduled service of odd numbered service routes and calculate the average obtained over all scheduled services of the service routes for each case. Considering only odd numbered service routes does not cause a loss of generality while reducing the total computation times significantly. We use the results to compare complete and partial replanning and examine how the trade-off between the two is affected under each scenario.

5.3.1 Partial vs Complete Replanning Under Multiple Cancellations (S3)

The results are presented in Table 7, where the third row shows the number of service cancellations occurring and fourth row the time (in hours) between consecutive cancellations. We first note that, for both replanning approaches, all total cost values are higher than that of the single cancellation scenario (S2), and cost values for 3 cancellations are higher compared to 2 cancellations. While partial replanning certainly achieves worse total cost values compared to S2, the performance of complete replanning is not noticeably affected. The difference between partial and complete replanning now becomes significant at 10% significance level for each number of disturbance and each time interval.

Table 7: Results summary for partial vs complete replanning under multiple service cancellations (S3)

	S3											
	Partial Replanning						Complete Replanning					
# Disturbances	#disturbances = 2			#disturbances = 3			#disturbances = 2			#disturbances = 3		
Time between	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs
Total Cost	681835.55	620614.75	761172.11	696497.33	675600.26	779666.07	387722.22	387843.64	388740.0	393022.39	394377.89	394565.39
NR1 CPU (s)	31.84	31.66	30.51	31.97	30.73	30.28	74.82	80.30	75.41	79.83	80.10	78.58
TM(1)(%)	43.35	43.31	43.43	43.08	43.20	43.38	43.08	43.05	43.13	42.59	42.47	42.35
TM(2)(%)	38.62	38.62	38.40	38.46	38.22	38.09	38.98	39.00	38.84	39.04	39.03	38.95
TM(3)(%)	18.02	18.07	18.18	18.46	18.57	18.53	17.93	17.95	18.03	18.36	18.50	18.70

Note that the number of affected shipments is the highest for 0 hours column and lowest for 48 hours column for each number of disturbance. The total cost values for partial replanning seem higher for 0 hours compared to 24 hours as more flows had to be rerouted. Yet the costs for 48 hours attain the highest values since the effects of the disturbances are more severe. This logically follows as imposing 48 hours time difference between two disturbances may result in a shipment having multiple disrupted arcs on its original shipment plan while this was limited to a single arc only with scenarios S1&S2. This in turn creates a more severe impact on the network. On the other hand, complete replanning does not seem to be troubled by the increase in disrupted flows. Next, we analyze the Performance Indicators in Table 8.

As expected, complete replanning accommodates significantly greater changes in shipment plans compared to partial planning. For complete replanning all PIs tend to increase as the number of hours between consecutive disturbances increase. Thus, the measures appear to be proportional to severity of affected shipments in terms of the number of disrupted arcs in the original shipment plan per shipment. However, we observe different patterns for partial replanning. Only the average unit shipment cost change $CC(\%)$ steadily rises with increasing hours between consecutive disturbances. The flows rerouted $FR(\%)$ are highest for 24 hours while lowest for 0 hours. This results from higher number of delayed shipments for 0 hours in the sense that at least some part of the demand had to be transported through the dummy arcs from origin

Table 8: Performance Indicators (PIs) for partial vs complete replanning under multiple cancellations (S3)

Replanning Approach	# Dist	Time Between	PI	Shipments										Average
				K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	
Partial	2	0 hrs	FR(%)	18.52	5.11	7.62	0	8.89	0	0	0	0	0	4.01
			CC(%)	14.94	3.18	3.53	0	14.38	0	0	0	0	0	3.6
			MS(%)	9.52	1.44	3.81	0	7.7	0	0	0	0	0	2.25
		24 hrs	FR(%)	19.74	5.79	7.14	0	8.22	0	0	0	0	0	4.09
			CC(%)	17.9	3.56	3.30	0	14.19	0	0	0	0	0	3.9
			MS(%)	9.68	1.67	3.57	0	7.6	0	0	0	0	0	2.25
		48 hrs	FR(%)	19.05	5.71	6.63	0	8.93	0	0	0	0	0	4.03
			CC(%)	21.28	3.43	3.07	0	14.64	0	0	0	0	0	4.24
			MS(%)	9.09	2.2	3.32	0	7.84	0	0	0	0	0	2.25
	3	0 hrs	FR(%)	28.5	7.15	7.47	0	10.08	0	0	0	1.01	1.01	5.52
			CC(%)	33.36	5.38	3.46	0	16.44	0	0	0	0	0	5.86
			MS(%)	13.08	2.27	3.73	0	8.8	0	0	0	0	0	2.79
		24 hrs	FR(%)	33.33	5.82	6.59	0	10.82	0	0	0	0	0.71	5.73
			CC(%)	39.98	4.02	3.05	0	17.74	0	0	0	0	0	6.48
			MS(%)	14.09	1.91	3.29	0	9.5	0	0	0	0	0	2.88
		48 hrs	FR(%)	31.58	4.74	7.14	0	8.22	0	0	0	0	1.32	5.3
			CC(%)	44.13	3.31	3.3	0	14.19	0	0	0	0	0	6.49
			MS(%)	14.3	2.2	3.57	0	7.6	0	0	0	0	0	2.77
Complete	2	0 hrs	FR(%)	18.89	7.78	7.94	0	8.89	0	0	0	7.41	0	5.09
			CC(%)	15.72	4.82	3.53	74.99	14.38	-25.65	0	0	0	0	8.78
			MS(%)	9.57	0	3.81	20.89	7.7	17.41	0	0	0	0	5.94
		24 hrs	FR(%)	19.74	8.68	7.52	0	8.22	0	0	0	8.33	0	5.25
			CC(%)	17.9	5.17	3.3	77.46	14.19	-26.5	0	0	0	0	9.15
			MS(%)	9.68	0	3.57	21.58	7.6	17.98	0	0	0	0	6.04
		48 hrs	FR(%)	19.64	19.64	19.64	41.43	16.52	37.2	0	0.2	11.31	4.85	17.04
			CC(%)	22.02	4.8	3.07	74.36	14.64	-25.44	0	0	0	0	9.35
			MS(%)	8.97	0	3.32	20.71	7.84	17.26	0	0	0	0	5.81
	3	0 hrs	FR(%)	28.89	25.18	21.01	42.66	16.86	36.79	0	0.46	10.34	7.64	18.98
			CC(%)	34.1	5.58	3.46	76.58	16.44	-26.2	0	0	0	0	11
			MS(%)	13.06	0	3.73	21.33	8.8	17.78	0	0	0	0	6.47
		24 hrs	FR(%)	33.57	22.3	19.6	43.97	19.24	, 38.89	0	0.24	8.39	8.41	19.56
			CC(%)	40.28	4.18	3.05	78.92	17.74	-27	0	0	0	0	11.72
			MS(%)	14.04	0	3.29	21.99	9.5	18.32	0	0	0	0	6.71
		48 hrs	FR(%)	32.46	22.24	19.36	46.05	15.46	41.89	0	0.22	13.6	6.2	19.75
			CC(%)	45.23	3.81	3.3	82.66	14.19	-28.28	0	0	0	0	12.09
			MS(%)	14.13	0	3.57	23.03	7.6	19.19	0	0	0	0	6.75

to destination terminal in order to meet the delivery time reqirements of the customers. If the delayed flows were taken into consideration when calculating the $FR(\%)$ values, we would see a steady increase as the hours increase, in which case it would correspond to a positive correlation with the number of affected commodities.

5.3.2 Partial vs Complete Replanning Under Multiple Delays (S4)

The results of multiple delays scenario are shown in Table 9 in a similar fashion to S3 scenario. The total cost for each column of both replanning approaches is lower than the total cost of corresponding columns in scenarios S2 and S3 while it remains higher than that of single disturbance scenario S1. Additionally, the difference between partial and complete replanning approaches becomes once again insignificant as it was for the single delay scenario.

Table 9: Results summary for partial vs complete replanning under multiple service delays (S4)

	S4											
	Partial Replanning						Complete Replanning					
# Disturbances	#disturbances = 2			#disturbances = 3			#disturbances = 2			#disturbances = 3		
Time between	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs
Total Cost	377266.67	377113.94	376920.0	378742.33	378311.13	378205.25	377192.82	377110.0	376896.3	378601.96	378266.95	378016.39
NR1 CPU (s)	26.53	23.1	23.01	25.87	25.93	26.19	74.75	75.77	74	76.73	73.82	74.43
TM(1)(%)	44.17	44.33	44.13	44.37	44.73	45.09	44.12	44.12	44.12	44.12	44.12	44.12
TM(2)(%)	38.99	38.85	38.77	38.90	38.64	38.52	39.12	39.20	39.19	39.14	39.26	39.21
TM(3)(%)	16.84	16.83	16.82	16.73	16.63	16.39	16.76	16.68	16.69	16.74	16.61	16.67

It again holds that the number of affected shipments is the highest for 0 hours and lowest for 48 hours for each number of disturbance while the severity of the affected shipments, in terms of disrupted arcs per commodity, is vice versa. We immediately see that the total costs are more in line with the total number of affected shipments than with the severity of the affected shipments such that they decrease as the number of hours increase. This results from the fact that multiple delays on the original arcs of a shipment do not crate noticeable additional damage as cancellations. Thus, the total cost is mostly driven by the number of affected shipments in total. This claim is supported by the performance measures in Table 10. The flows rerouted $FR(\%)$ and the average unit shipment cost change $CC(\%)$ show a similar decreasing pattern, with respect to (increasing) hours, for both replanning approaches as anticipated. Finally, we again see greater changes in shipment plans of complete replanning compared to partial planning.

Table 10: Performance Indicators (PIs) for partial vs complete replanning under multiple delays (S4)

Replanning Approach	# Dist	Time Between	PI	Shipments										Average
				K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	
Partial	2	0 hrs	FR(%)	28.46	7.32	6.27	0	7.32	0	0	0	3.25	4.18	5.68
			CC(%)	7.27	0.36	0.53	0	0.92	0	0	0	0.18	0.86	1.01
			MS(%)	1.08	0	0	0	0	0	0	0	0	0	1.08
		24 hrs	FR(%)	33.33	8.48	6.93	0	7.58	0	0	0	0	0	5.63
			CC(%)	7.54	0.44	0.66	0	1	0	0	0	0	0	0.96
			MS(%)	1.68	0	0	0	0	0	0	0	0	0	1.68
		48 hrs	FR(%)	33.33	7.59	5.91	0	7.76	0	0	0	0	0	5.46
			CC(%)	6.89	0.50	0.75	0	0.81	0	0	0	0	0	0.9
			MS(%)	1.53	0	0	0	0	0	0	0	0	0	1.53
	3	0 hrs	FR(%)	32.46	9.42	7.16	0	9.67	0	0	0	1.40	3.78	6.39
			CC(%)	12.10	0.50	0.81	0	1.45	0	0	0	0.09	0.92	1.59
			MS(%)	1.33	0	0	0	0	0	0	0	0	0	1.33
		24 hrs	FR(%)	39.33	8.20	7.05	0	9.62	0	0	0	0	0.84	6.5
			CC(%)	10.70	0.68	1.05	0	1.38	0	0	0	0	0	1.38
			MS(%)	2.37	0	0	0	0	0	0	0	0	0	2.37
		48 hrs	FR(%)	40.44	9.18	5.62	0	6.97	0	0	0	0	1.64	6.39
			CC(%)	10.14	1.34	0.99	0	1.00	0	0	0	0	0	1.35
			MS(%)	1.82	0	0	0	0	0	0	0	0	0	1.82
Complete	2	0 hrs	FR(%)	29.91	10.26	9.16	36.41	7.69	31.62	0	0	12.82	9.52	14.74
			CC(%)	7.64	0.22	0.56	65.35	0.97	-22.36	0	0	0.37	0.45	5.32
			MS(%)	1.14	0	0	18.21	0	15.17	0.0	0	0	0	3.45
		24 hrs	FR(%)	34.38	11.25	8.93	31.88	7.03	28.65	0	0	9.38	7.59	13.91
			CC(%)	7.77	0.36	0.68	57.21	0.88	-19.57	0	0	0	0	4.73
			MS(%)	1.74	0	0	15.94	0	13.28	0	0	0	0	3.1
		48 hrs	FR(%)	35.80	10.37	7.41	31.11	7.41	27.16	0	0	6.17	7.41	13.28
			CC(%)	7.40	0.32	0.61	55.84	0.70	-19.10	0	0	0	0	4.58
			MS(%)	1.65	0	0	15.56	0	12.96	0	0	0	0	3.02
	3	0 hrs	FR(%)	33.06	14.16	9.30	37.88	9.80	33.47	0	0	8.91	9.24	15.58
			CC(%)	12.06	0.30	0.80	67.99	1.45	-23.26	0	0	0.16	0.47	6
			MS(%)	1.36	0	0	18.94	0	15.78	0	0	0	0	3.61
		24 hrs	FR(%)	39.33	9.46	8.37	36.40	9.62	32.91	0	0	4.74	8.31	14.91
			CC(%)	10.70	0.55	1.05	65.34	1.38	-22.35	0	0	0	0	5.67
			MS(%)	2.37	0	0	18.20	0	15.17	0	0	0	0	3.57
		48 hrs	FR(%)	40.44	12.62	6.09	34.10	6.97	31.42	0	0	2.19	8.43	14.22
			CC(%)	10.14	0.77	0.99	61.20	1.00	-20.94	0	0	0	0	5.32
			MS(%)	1.82	0	0	17.05	0	14.21	0	0	0	0	3.31

5.3.3 Partial vs Complete Replanning Under Cancellation and Delay (S5)

We now analyze the combination of cancellations and delays (of 6 hours) in the planning horizon. The results for 2 disturbances (1 cancellation and 1 delay) for different number of hours are shown in Table 11. For the sake of brevity, we exclude the results for 3 disturbances (1 cancellation and 2 delays) as the emerged patterns are very similar and do not necessitate additional analysis.

We now see steady increase in total cost values as the number of hours increase for both replanning approaches as was the case for complete replanning in multiple cancellations scenario S3. This implies that partial replanning is not critically affected by the increased number of affected shipments as long as the number of cancellations is limited to 1. Both partial and complete replanning total costs in S5 appear to be an approximate average of the two previous scenarios S3 and S4 as expected. The increasing pattern of total costs is sustained in Performance Indicators

Table 11: Results summary for partial vs complete replanning under S5

	S5					
	Partial Replanning			Complete Replanning		
Time between	0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs
Total Cost	564977.65	568353.94	575233.10	387157.33	387684.21	388100.69
NR1 CPU (s)	32.15	33.29	35.74	76.96	77.57	78.08
TM(1)(%)	42.94	42.74	42.74	42.50	42.37	42.33
TM(2)(%)	39.21	39.38	39.27	39.75	39.88	39.84
TM(3)(%)	17.85	17.87	17.93	17.75	17.75	17.83

in Table 12. The flows rerouted $FR(\%)$ and average unit shipment cost change $CC(\%)$ values increase together with increasing hours between for both replannings.

Table 12: Performance Indicators (PIs) for partial vs complete replanning under S5

Replanning Approach	Time Between	PI	Shipments										Average
			K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	
Partial	0 hrs	FR(%)	31.48	7.22	7.14	0	8.33	0	0	0	0	0	5.42
		CC(%)	29.93	0.95	1.47	0	9.59	0	0	0	0	0	4.19
		MS(%)	14.28	0.53	1.59	0	5.13	0	0	0	0	0	2.15
	24 hrs	FR(%)	33.33	7.27	6.93	0	7.58	0	0	0	0	0	5.51
		CC(%)	32.81	1.04	1.6	0	9.15	0	0	0	0	0	4.46
		MS(%)	15.33	0.58	1.73	0	4.9	0	0	0	0	0	2.25
	48 hrs	FR(%)	33.33	6.21	5.91	0	7.76	0	0	0	0	0	5.32
		CC(%)	35.85	1.18	1.82	0	7.44	0	0	0	0	0	4.63
		MS(%)	14.98	0.66	1.97	0	3.98	0	0	0	0	0	2.16
Complete	0 hrs	FR(%)	32.41	24.72	13.49	30	13.19	25.93	0	0	5.56	7.54	15.28
		CC(%)	32.04	1.72	1.49	53.85	9.59	-18.42	0	0	0	0	8.03
		MS(%)	14.05	0	1.59	15	5.13	12.5	0	0	0	0	4.83
	24 hrs	FR(%)	33.33	23.94	14.29	30.91	12.88	26.77	0	0	3.03	8.66	15.38
		CC(%)	32.81	1.88	1.6	55.48	9.15	-18.98	0	0	0	0	8.19
		MS(%)	15.33	0	1.73	15.45	4.9	12.88	0	0	0	0	5.03
	48 hrs	FR(%)	33.33	20.34	12.32	28.97	12.07	25.86	0	0	6.9	8.37	14.82
		CC(%)	35.85	2.14	1.82	51.99	7.44	-17.79	0	0	0	0	8.15
		MS(%)	14.98	0	1.97	14.48	3.98	, 12.07	0	0	0	0	4.75

Although the difference between partial and complete replanning is greater compared to delay scenarios, it is not significant like in multiple cancellation scenario. Thus, the trade-off between running time and lower costs once again comes forward.

5.3.4 Partial vs Complete Replanning Under Multiple Cancellation (S3) and More Commodities

Finally, we test multiple cancellations scenario on 20 commodities. The first 10 commodities are the same as before, and the additional 10 commodities are summarized in Table 17 in the appendix. The results for 2 disturbances are shown in Table 13, where S0 stands for the shipment plan for 20 commodities under no disturbances.

Surprisingly, partial replanning is not notably affected by the disturbances when the number of commodities doubled. The reason behind this counter-intuitive outcome is that the shipments are now more dispersed over the network, and every pair of disturbances impacts a lower percentage of the demand flow. Furthermore, the total costs for partial and complete replanning are very similar. We look at Table 14 for more insight on the differences between two replannings. Note that the PIs for only first 10 commodities are reported as this does not change the conclusions drawn and avoids excessive information.

Table 13: Results summary for partial vs complete replanning under S3 and 20 more commodities

	S0	S3 with 20 commodities					
		Partial Replanning			Complete Replanning		
Time between		0 hrs	24 hrs	48 hrs	0 hrs	24 hrs	48 hrs
Total Cost	705160.0	719072.79	720042.58	721103.53	718744.91	719926.88	721055.88
NR1 CPU (s)	183.33	53.65	50.47	50.89	179.83	172.46	175.25
TM(1)(%)	48.11	47.36	47.43	47.38	47.41	47.46	47.47
TM(2)(%)	28.30	28.24	28.06	28.16	28.28	28.18	28.12
TM(3)(%)	23.58	24.40	24.50	24.46	24.31	24.36	24.40

Table 14: Performance Indicators (PIs) for partial vs complete replanning under S3 and more demand

Replanning Approach	Time Between	PI	Shipments										Average
			K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	
Partial	0 hrs	FR(%)	11.11	4.91	3.26	0	7.46	0	0	0	2.05	2.63	3.14
		CC(%)	6.8	6.06	1.33	0	11.35	0	0	0	0.03	0	2.56
		MS(%)	4.99	1.93	1.63	0	6.08	0	0	0	0.29	0	1.49
	24 hrs	FR(%)	12.9	5.16	3.99	0	7.53	0	0	0	0	1.08	3.07
		CC(%)	8.96	6.37	1.63	0	11.6	0	0	0	0	0	2.86
		MS(%)	5.51	2.02	2	0	6.21	0	0	0	0	0	1.57
	48 hrs	FR(%)	13.73	4.71	4.62	0	7.35	0	0	0	0	1.47	3.19
		CC(%)	10.14	5.81	1.89	0	12.05	0	0	0	0	0	2.99
		MS(%)	5.2	1.85	2.31	0	6.45	0	0	0	0	0	1.58
Complete	0 hrs	FR(%)	12.87	, 5.26	32.71	35.96	9.98	21.49	40.7	1.85	6.14	4.14	17.11
		CC(%)	7.15	2.57	2.44	-0.18	11.35	10.14	-5.46	0.05	0	0	2.81
		MS(%)	5.83	0.45	3.11	5.53	6.08	7.24	5.2	0.19	0	0	3.36
	24 hrs	FR(%)	13.26	5.59	29.34	32.69	10.22	25.63	36.13	1.79	3.76	2.15	16.06
		CC(%)	8.72	2.25	2.36	-2.92	11.6	12.6	-5.66	0.07	0	0	2.9
		MS(%)	5.61	0.4	3.07	5.27	6.21	7.71	5.35	0.24	0	0	3.39
	48 hrs	FR(%)	13.73	5	23.32	57.06	7.72	29.66	39.41	4.25	4.9	3.15	18.82
		CC(%)	10.85	0.61	2.21	0.31	12.05	4.07	-8.87	0.05	0	0	2.13
		MS(%)	5.24	0.11	2.84	6.62	6.45	6.5	8.49	0.16	0	0	3.64

The average unit shipment cost change $CC(\%)$ and modal split $MS(\%)$ per commodity values for the two replanning approaches follow each other closely, and we do not note any statistical difference. Flows rerouted $FR(\%)$, however, is much higher for complete planning for each number of hours. Since there is no significant difference in total costs, complete replanning seems to carry out unnecessary modifications, which would create inconvenience if the costs of changing course for a shipment were not neglected. Also being 3 times faster, partial replanning, thus, becomes the dominant option in this setting.

6 Conclusion

In this paper, we examined the Transportation Replanning Problem (TRP) for path-flow based multi-commodity intermodal networks to find minimum cost shipment plan after the occurrence of a disturbance. We build on the work of Akyüz et al. (2022), which proposes a tailored Column Generation (CG) algorithm to solve the constrained model, (M), using two different replanning approaches: complete and partial replanning. Complete replanning solves the model (M) from scratch every time a disturbance occurs while partial replanning solves it only for the disrupted shipment flow, hence, creating a powerful difference in solution speed. However, partial replanning tends to produce inferior results in terms of total transportation costs in many experiments as it lacks the flexibility of complete replanning. Thus, we recognize a trade-off between the two approaches in terms of speed and total costs.

Akyüz et al. (2022) examine the status of the network and the performances of the replanning approaches under 2 different disturbance scenarios. The first scenario, S1, considers a single service delay throughout the planning horizon for different delay durations (2 to 12 hours), and the second scenario, S2, considers a single service cancellation. The model is tested using a European intermodal logistic network on an extensive set of experiments mimicking real-life (Akyüz et al., 2022). We replicate the experiments using the same network setting and summarize their main findings. In scenario S1, there is little to no difference in total costs of the two replanning approaches. Although the difference in total cost values are notably higher in the cancellation scenario, S2, they are nevertheless not statistically different under significance level of 10%. Therefore, the choice between the two approaches remains case specific and a matter of priorities.

We extend the work of Akyüz et al. (2022) by studying multiple disturbance scenarios: scenario S3 for multiple service cancellations, scenario S4 for multiple service delays (of 6 hours) and scenario S5 for both cancellations and delays. In each scenario, the number of disturbances varies between 2–3 and the time interval between two consecutive disturbances varies between 0–48 hours as a multiple of 24 hours. Our results indicate that the two replanning approaches may display different patterns under different scenarios, e.g. in S3 the total costs for partial replanning are largely driven by the total number of affected shipments while the total costs for complete replanning remains in line with the number of affected arcs per affected shipment, namely, the severity of the disturbance. We also observe that both replannings are driven by the total number of affected shipments under S4 and by the severity of the disturbance under S5. Using a t-test of 10% significance level, we conclude that the difference between total costs of the two approaches is significant only for S3. On the other hand, complete replanning reroutes substantially more flows than partial replanning in each scenario. Finally we test the multiple cancellation scenario S3 using 10 additional commodities. Surprisingly, partial replanning catches up with complete replanning in total cost values, and renders itself the dominant approach considering its obvious advantage in speed.

This study provides strong evidence that partial replanning can still be applied in most cases although it generates higher costs than complete replanning. A valuable future research would be combining the two replanning approaches, e.g an intermediate approach that re-routes both the shipments affected from a disruption and the shipments that have room for re-routing, in order to utilize the speed advantage of partial replanning while maintaining minimal transportation plan costs.

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Appendices

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

```
Input: Origin node $o$, destination node $d$, graph $\mathcal{G} = (\mathcal{N}; \mathcal{A})$, cost weights $c_{ij}^k$;
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 $i \in \{\mathcal{N} \backslash o\}$ and $\mathcal{Q} = \emptyset$;
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 $p^*$;
Label Correction: Set $\mathcal{N}_i = \{j : (i,j) \in \mathcal{A}\}$.
for $j \in \mathcal{N}_i$ do
    if $T_i^{\ell^*} + t_{ij} \leq T_{max}^k$ and $F_i^{\ell^*} + f_{ij} \leq F_{max}^k$ then
        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
            $\mathcal{L}^j = \{\mathcal{L}^j \backslash \ell'\}$ and $\mathcal{L} = \{\mathcal{L} \backslash \ell'\}$;
if Step 7 holds for at least one label then
    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 $\ell^*$ of node $i$ as the preceding label of $\bar{\ell}$ and set $\mathcal{Q} = \{\mathcal{Q} \cup \bar{\ell}\}$;
    if Node of $\bar{\ell} \neq d$ then
        Set $\mathcal{L} = \{\mathcal{L} \cup \bar{\ell}\}$ and $\mathcal{L}^j = \{\mathcal{L}^j \cup \bar{\ell}\}$;
Go to Step 3.
```

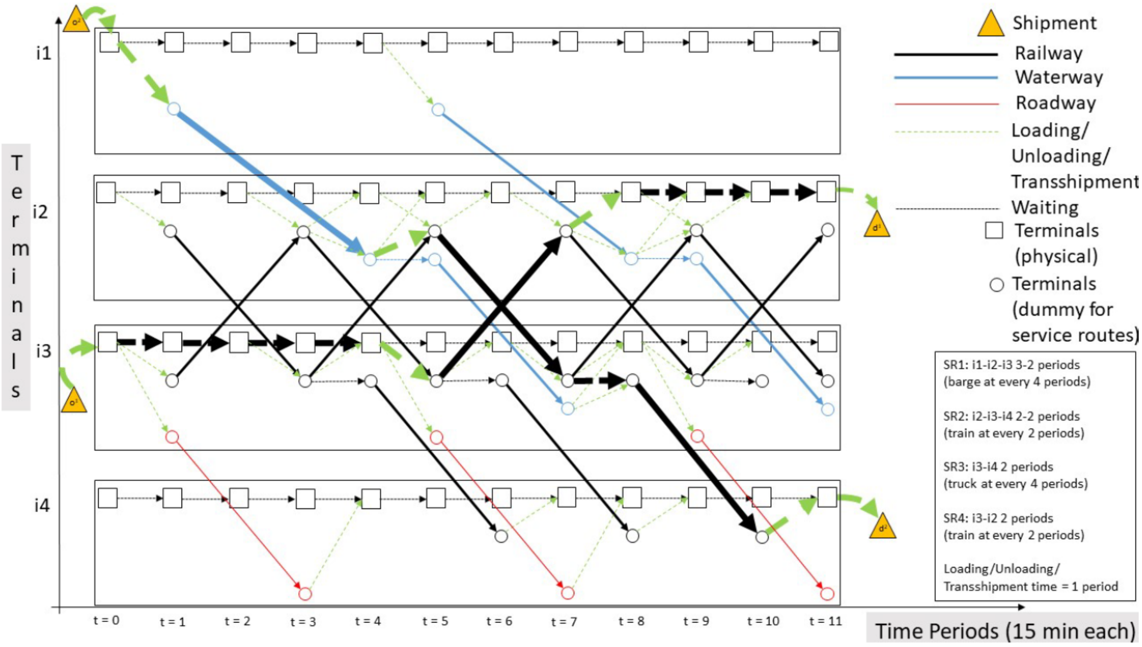

Figure 2: Time-space network representation NR1 (Akyüz et al., 2022).

Table 15: Description of the service routes (SRs) by Akyüz et al. (2022)

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,. . . ,61}	80	Waterway
SR3-4	Rotterdam $\xrightarrow{(8)}$ Antwerp	{1,7,13,. . . ,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,. . . ,61}	40	Railway
SR17-18	Hull $\xrightarrow{(11)}$ Rotterdam	{1,3,5,. . . ,61}	–	Roadway
SR19-20	Rotterdam $\xrightarrow{(9)}$ Mannheim	{1,3,5,. . . ,61}	–	Roadway
SR21-22	Rotterdam $\xrightarrow{(2)}$ Duisburg	{1,3,5,. . . ,61}	–	Roadway
SR23-24	Duisburg $\xrightarrow{(10)}$ Prague	{1,3,5,. . . ,61}	–	Roadway
SR25-26	Hamburg $\xrightarrow{(9)}$ Prague	{1,3,5,. . . ,61}	–	Roadway
SR27-28	Duisburg $\xrightarrow{(3)}$ Hamburg	{1,3,5,. . . ,61}	–	Roadway
SR29-20	Rotterdam $\xrightarrow{(4)}$ Hamburg	{1,3,5,. . . ,61}	–	Roadway
SR31-32	Rotterdam $\xrightarrow{(13)}$ Lyon	{1,3,5,. . . ,61}	–	Roadway
SR33-34	Duisburg $\xrightarrow{(6)}$ Mannheim	{1,3,5,. . . ,61}	–	Roadway

Table 16: Origin and destination terminals, and demand quantities of shipments (Akyüz et al., 2022)

Shipment	Origin	Destination	Unit
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

Table 17: Origin and destination terminals, and demand quantities of additional shipments

Shipment	Origin	Destination	Unit
K11	Rotterdam	Antwerp	100
K12	Rotterdam	Hull	120
K13	Rotterdam	Mannheim	120
K14	Prague	Hamburg	140
K15	Duisburg	Rotterdam	100
K16	Prague	Antwerp	60
K17	Prague	Lyon	80
K18	Hamburg	Duisburg	60
K19	Hull	Antwerp	100
K20	Antwerp	Hamburg	40