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Evaluating the cost-emissions trade-offs of a modal shift in intermodal and synchronomodal transportation planning

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Abstract

Intermodal transportation planning combines road with more sustainable transportation modes to encourage a modal shift. To evaluate the impact of a modal shift on transportation cost and emissions, we propose an intermodal transportation planning model to provide transparency in the cost-emissions trade-off. The model incorporates minimum load requirements, time windows, freight consolidation, and stochastic travel times to generate alternative transportation options. It also includes order consolidation to facilitate the utilization of transportation modes that would otherwise be infeasible due to, for instance, minimum load requirements. We also propose a synchronomodal planning tool to evaluate re-planning and re-consolidation options in response to disruptions. We numerically illustrate the working of our model using a representative network setting and quantify the trade-offs concerning costs and emissions by evaluating different transportation route options.

Keywords: synchronomodal transportation, modal shift, sustainable transportation, decision support, k -shortest path, order consolidation

1. Introduction

Unless the coming decades see significant reductions in greenhouse gas (GHG) emissions, it is believed that global warming of 1.5°C - 2°C will be exceeded during the 21st century (The Intergovernmental Panel on Climate Change 2021). To keep the Paris Agreement's (United Nations Climate Change 2015) maximum global warming target of 1.5°C within reach, multiple world leaders have committed to securing global net zero carbon emissions by 2050 at the 2021 United Nations Climate Change Conference (UN Climate Change Conference 2021). Given this global commitment to net zero emissions amid the worrying trend

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of climate change, industrial sectors are increasingly under pressure to reduce their carbon footprint. In particular, freight transportation accounted for an estimated 7% of total global GHG emissions in 2017 (International Transport Forum 2017), with the logistics freight supply chain identified as one of the eight most polluting supply chains in the world (World Economic Forum and Boston Consulting Group 2021). Should current practices remain unchanged, freight transportation is predicted to be the largest emitting sector by 2050 (Rogelj et al. 2018). In addition, Ellram et al. (2022) highlighted that firms generally take limited responsibility for transportation emissions, especially when freight transportation is outsourced. Accordingly, there is an opportunity to decarbonize logistics via improved freight transportation planning (Demir et al. 2022), which also forms part of the United Nations Sustainable Development Goal (UN SDG) 13, named climate change (United Nations Sustainable Development 2015) and the European Commission’s aims to cut freight transportation emissions by at least 60% by 2050 (European Commission 2011). As the need for freight transportation remains and is expected to grow (World Economic Forum 2020, Ellram et al. 2022), part of the transportation emissions are unavoidable (World Economic Forum and Boston Consulting Group 2021). Such unavoidable emissions can be addressed by zero-emission fuel and shifting to low- and zero-emission vehicles, such as electric vehicles, but this comes at high investment costs. On the other hand, some transportation emissions are avoidable and result from inefficient business-as-usual. Addressing these avoidable emissions should be obtainable at a lower investment cost than addressing unavoidable emissions. We focus on reducing avoidable transportation emissions, aiming to shift freight away from roads towards alternative, more sustainable transportation modes. Shifting freight from road to alternative modes is called a modal shift. This approach falls within both the ‘avoid’ and ‘shift’ elements of the avoid-shift-improve framework to reduce transportation emissions (European Environmental Agency 2022).

To date, the most widely used transportation mode for continental freight shipments in Europe is road, accounting for more than 70% of overall tonne-kilometers (European Union 2020). Hence, a shift towards alternative modes immediately reduces freight transportation’s emissions, as it is well known that rail and waterway transportation is more sustainable than road transportation (Otten 2021). Two freight transportation strategies, namely intermodal and synchromodal transportation, encourage a modal shift. In intermodal transportation, freight is moved through a network using an intermodal container and multiple transportation modes (Bontekoning et al. 2004). The combination of modes used in intermodal transportation, such as waterways, railways, and roads, can reduce freight transportation costs compared to using roads alone, referred to as unimodal road transportation. However, alternative modes used in intermodality are generally slower than road transportation, often experience operational delays, and pose several inflexible restrictions, such as minimum load requirements and fixed service departure schedules. Minimum load requirements may be addressed via order consolidation, but intermodal freight transportation planning is particularly rigid when delays occur. The reason is that intermodal transportation follows a fixed, predetermined route, so delays may result in missed mode transfers due to departure schedule restrictions and, ultimately, late deliv-

eries. Synchronodal transportation attempts to overcome the rigidity of intermodal solutions by addressing the service schedule inflexibility. Whereas intermodal routes are predetermined and fixed, synchronodal planning allows for changes to the predetermined route in response to real-time travel time information and route disruption updates (Tavasszy et al. 2010). Successful synchronodal transportation implementation, however, is dependent on real-time shipment tracking and digital decision support software, as supported by the Physical Internet (PI) (Montreuil 2011a, Dong & Franklin 2021, Plasch et al. 2021). The PI was introduced to transition towards interconnected logistics operations and supply chain networks (Montreuil 2011b, Sarraj et al. 2014, Ballot et al. 2021, Dong & Franklin 2021). It is based on integrating various logistics services and networks, including freight transportation and facilities. The integration required for synchronodal transportation also necessitates coordination between the relevant stakeholders. We refer the interested reader to the work of Giusti et al. (2019b), who elaborate on the importance of stakeholder coordination for synchronodal planning.

With our work, we aim to stimulate the reduction of avoidable freight transportation emissions using intermodal and synchronodal solutions. The work is inspired by our participation in a national research project in which several Belgian small-medium enterprises, consisting of logistics service providers (LSPs) and information technology companies, are involved. Until recently, the project participants' main focus was minimizing the cost of their transportation solutions. Their customers drove this cost focus. This route, however, may not be preferred from an emissions perspective. The latter is gaining traction because today, companies above a specific size must report on their sustainability performance under the Corporate Sustainable Reporting Directive (CSRD). This European legislation pushes the entire market towards greening and transparency, which is also felt in the transportation sector. But optimizing for emissions may increase costs, as cost and emissions may be inversely related across transportation modes, and the preferred route from an emissions perspective may require additional transshipment costs. Hence, intermodal routes minimizing emissions may still be rejected by a decision maker, especially when compared to a cost-minimizing route.

We propose a method to provide transparency into the trade-offs between the conflicting objectives of minimizing costs and emissions. To do so, we develop a k -shortest path model to determine various intermodal routing solutions, with a synchronodal module to replan when delays occur along the route. Our model provides a transportation planner with the cost-minimizing solution and a set of alternative, lower-emission transportation solutions whose total cost falls within a pre-specified maximum cost bound, determined in relation to the minimum cost solution. Such a cost bound allows us to examine multiple shipment route options whose cost falls within this bound and results in reduced emissions. This approach will enable us to quantify the emissions benefits that may be achieved at a (controlled) increase in freight transportation costs. With Environmental, Social, and Governance (ESG) aspects becoming more critical, companies may deviate from their original cost-only focus that, until recently, dominated the logistics industry.

Ellram et al. (2022) emphasized the need to create visibility of freight transportation emissions and highlighted the lack of Scope 3 emissions considerations, including outsourced freight transportation. Our

cost-bound method enables insight into the cost-emissions trade-off of more carbon-friendly alternative solutions. We believe that transportation planners may be more amenable to adopting (and/or proposing to their customers) emission-focused solutions when the trade-offs are more transparent. This approach may facilitate the adoption of alternative transportation solutions other than the cost-minimizing solution and support the shift towards more sustainable transportation operations. In addition, the synchromodal replanning module allows for responding to delays in transportation services. This replanning may help improve on-time delivery when using sustainable transportation modes to overcome the disadvantage of their lower reliability.

We illustrate the application of our model for a European intermodal transportation network consisting of road, railway, and inland waterway transportation. While this case study allows us to evaluate the cost-emissions trade-offs between various transportation solutions for this network, the model may be extended to other intermodal networks and larger network sizes (at, naturally, increasing running time requirements). Our numerical example shows, for instance, how a cost bound as low as 10% per shipment above the minimum cost option may already lead to meaningful freight emission reductions. We show how further emission reductions can be achieved even within a limited cost increase. Transportation planners may find these solutions more accessible than implementing the lowest-emissions solution. In addition, our numerical results show how synchromodal replanning can improve reliability over the intermodal solution by ensuring on-time delivery when delays occur.

2. Literature review

We create transparency in the cost-emissions trade-offs through a k -shortest path intermodal transportation model that generates alternative transportation route options. Moreover, we use real-time information to update the intermodal shipment planning, known as synchromodal transportation. Synchromodality constitutes an integral pillar in the transition towards the Physical Internet of logistics operations, along with improved coordination and collaboration along and across supply chain networks (ALICE 2014, 2021). The concept of synchromodality was coined in 2010 by Tavasszy et al. (2010). This section reviews work on synchromodal transportation planning and its potential to reduce avoidable freight transportation emissions. We refer the interested reader to Bontekoning et al. (2004) and SteadieSeifi et al. (2014) for comprehensive reviews on intermodal transportation and Giusti et al. (2019b), Ambra et al. (2019b), Delbart et al. (2021) and Rentschler et al. (2022) on synchromodal transportation.

Research on synchromodal transportation typically consists of reactive or proactive decision-making approaches. The proactive synchromodal approach may be defined as preparing alternative routes in case of future disruptions when determining an order's initial transportation plan. Examples of such a proactive synchromodal transportation approach are provided in Yee et al. (2021) and Rivera & Mes (2022).

We consider reactive synchromodal transportation planning in this work. The reactive synchromodal approach may be decomposed into two phases: an initial intermodal planning phase and a reactive synchro-

modal re-planning phase. In the intermodal phase, an intermodal transportation plan is determined and implemented for all orders while disregarding the likelihood of a disruption. Should an order’s route be disrupted, the synchronomodal phase adapts the affected transportation plans accordingly. Hrušovský et al. (2021) first schedule a shipment using an intermodal model, after which they use a simulation-optimization model to re-plan a scheduled shipment when a disruption occurs on a segment not yet visited. Their replanning approach constitutes three policies. These are either to do nothing and wait until the disruption is resolved, transshipping before reaching the disturbed route segment, or bypassing the segment with the shortest path detour. Their model recommends a single option, minimizing the expected cost. In Van Riessen et al. (2015), Ambra et al. (2019a) and Giusti et al. (2019a), synchronomodal transportation is modeled in reaction to disturbances experienced during a shipment’s transit. Van Riessen et al. (2015) perform periodic synchronomodal re-planning of all in-transit shipments using known route disturbances at the re-planning decision moment. Both Ambra et al. (2019a) and Giusti et al. (2019a) evaluate the benefit of synchronomodal transportation in terms of route reliability based on risk factors such as the probability of a disruption on a specific segment along with its severity in terms of duration. Guo et al. (2020) consider a rolling time horizon for dynamically rescheduling shipments using an online platform for an inland synchronomodal network. The authors minimize transportation costs. Guo et al. (2021) extend the setting to global synchronomodal transportation with uncertainty regarding incoming shipments.

These works typically focus on optimizing synchronomodal transportation by minimizing costs for a single shipment and providing the best solution. Efficiencies (in terms of transportation costs, emissions, or both) may be lost by not considering order consolidation, both at the initial planning and rescheduling phases. In addition, alternative solutions to the single best solution can provide insight to a decision-maker on marginal trade-offs between cost increases, emissions reductions, and route reliability. We next highlight work focusing on reducing emissions, consolidating orders and/or providing multiple solutions to a planner.

Emission reduction. The majority of research on synchronomodal transportation planning focuses on minimizing costs. Transportation planning focusing on sustainability is still limited. Where emissions are considered, these are typically either modeled as a cost parameter and included in the objective function minimizing costs (as in Ambra et al. (2019a)) or used in multi-objective decision-making models as a secondary objective to minimizing costs (as in Resat & Turkay (2019), Larsen et al. (2021)). Resat & Turkay (2019) consider cost, time, and emissions in their multi-objective formulation for synchronomodal transportation, using the ϵ -constraint method to provide a single solution to the decision maker. The authors consider road, railway, and sea transportation for less-than-container load (LCL) shipments, using stochastic travel time for road only. Larsen et al. (2021) develop an integrated mode choice and vehicle routing model for container transportation. Their analysis considers multiple road legs and only one sea and railway leg. Their proposed method and assumptions increase truck utilization (especially concerning empty backhauls) while reducing the amount of cargo shipped by rail. The increased truck utilization translates into fewer truck miles driven and, hence, reduced transportation emissions, compared to a two-stage model that optimizes transportation mode and

route choices separately. Alternatively, Heinold & Meisel (2020) evaluate the effect of imposing emissions limits on a set of orders in an intermodal transportation network. They evaluate the use of payload-based and egalitarian emissions allocation strategies. Considering road and railway transportation, the authors solve the problem for cost, emissions, and service objectives. They find that the solution that minimizes the number of orders that exceed their emission limits differs from the solution that minimizes either total emissions or total costs. The authors determine a single solution for a set of orders and do not consider synchromodal transportation.

Order consolidation. Order consolidation bundles shipments to achieve larger shipment volumes. Our work considers order consolidation of full container loads (FCL). Since railways and waterways generally require large shipment volumes to obtain economies of scale or even impose minimum load requirements, a common barrier to the modal shift is the low volume of shipments. Collaborative shipments of FCLs solve this problem and may facilitate the modal shift. Work considering both synchromodal transportation planning and order consolidation, yet recommending a single route to the decision-maker, include Rivera & Mes (2017), Dong et al. (2018), Lemmens et al. (2019) and Qu et al. (2019). While Rivera & Mes (2017) focus on bundling shipments within transportation capacity limits, Dong et al. (2018), Lemmens et al. (2019) and Qu et al. (2019) additionally consider the splitting of shipments over different transportation services. Neither of the models consider re-consolidating freight upon re-planning in their synchromodal model. In Van Heeswijk et al. (2018), the authors consider an intermodal transportation problem in which they evaluate the effect of consolidation for LCL load shipments. Specifically, they evaluate order consolidation opportunities using decision trees that minimize cost and consider the best k routes for each order. They do not consider synchromodality. Rivera & Mes (2022) use an MDP for synchromodal transportation planning with consolidation, providing a single solution over a relatively small network. Ambra et al. (2021) consider order consolidation for road transportation using the Physical Internet. While not directly considering emissions, their work improves vehicle utilization and reduces distances driven, therefore indirectly positively impacting emissions.

Multiple route options. Work providing multiple route options to a decision-maker includes Mes & Iacob (2016) and Giusti et al. (2019a). Mes & Iacob (2016) determine k -shortest routes for a single shipment given user-defined weights as a multi-objective model minimizing costs, delays, and emissions. The work of Giusti et al. (2019a) is also based on user-defined weights and additionally includes route reliability, such as the probability of a shipment arriving late. Neither Giusti et al. (2019a) nor Mes & Iacob (2016) consider freight consolidation. Additionally, Mes & Iacob (2016) do not consider real-time information for synchromodal route updating. In their multi-objective approaches, Giusti et al. (2019a) use simulation optimization and Mes & Iacob (2016) develop heuristics to solve their respective models for realistically sized problems.

Despite the research on reducing emissions via either synchromodality, order consolidation, or multiple route options, we are unaware of research incorporating all three components. Our work integrates all three facets, leveraging the benefits of incorporating freight consolidation in synchromodal transportation planning

with multiple route options to reduce transportation emissions further. We allow order consolidation in the initial intermodal transportation planning and synchronodal updating phases. Freight consolidation upon shipment delays allows further opportunities to reduce transportation costs and emissions. Our solution model proposes up to k alternative route options with lower estimated emissions when compared to the minimum cost solution to decision-makers, considering lead time and cost constraints. This enables us to quantify the cost-emission trade-offs of carbon-friendly alternative solutions. Making these trade-offs transparent may stimulate a modal shift as it may elucidate how emissions can be reduced at only modest cost increases.

3. Problem description

The problem setting we consider can be described as follows. Consider an LSP transportation planner responsible for determining the transportation route for a set of incoming freight orders. Orders can originate from various customers, who outsource the transportation planning to the LSP planner. Each incoming order has specific characteristics, as specified by the customer, such as order size, release date, delivery date, origin, and destination. We let the order size be measured in full container loads (FCL) of twenty-foot equivalent unit (TEU) containers. The release date is when the order is available for pickup and shipment at the origin. The longer the time between the date the order is received and its release date, the more time the planner has to assign the order to an intermodal transportation route. The delivery date is the latest date the order is due at its destination. The time between the release and delivery date is the delivery time window.

To determine an order’s transportation route, the LSP planner has access to a multimodal network. Such a multimodal transportation network consists of several hubs connected by multiple transportation modes. We refer to the connection between two specific hubs as a transportation leg, and a single specific transportation mode represents every transportation leg. Hence, a leg for a specific transportation mode exists between two hubs in a network only if that mode is available to ship freight between those two hubs. An order originates at, and is destined for, one of the hubs in the network and can only switch transportation modes at a hub, referred to as a transshipment. Hubs may, therefore, represent an order’s origin, destination, or transshipment facility. An order’s transportation route is constructed by selecting a sequence of transportation legs linked by hubs to connect its origin with its destination. When executing the route, the order is shipped along the selected transportation legs and passes through the connecting hubs, potentially with transshipment in those hubs. Each leg in a network has a distance, cost, emissions, expected travel time, and minimum load restrictions associated with it. We define the expected travel time over a given leg in the network as the average travel time of the leg’s transportation mode. In addition, on each leg, a service schedule determines the departure time and frequency that a transportation service is available on the leg.

The transportation modes considered in this work concern inland freight transportation modes, which include road, railway, and inland waterway. By means of illustration, Figure 1 visualizes such a multimodal transportation network consisting of five hubs connected by transportation legs of the three inland transportation modes. For illustrative purposes, we list three different transportation routes for the network in

Figure 1, each of which optimizes a different objective, namely transportation time, cost, and emissions.

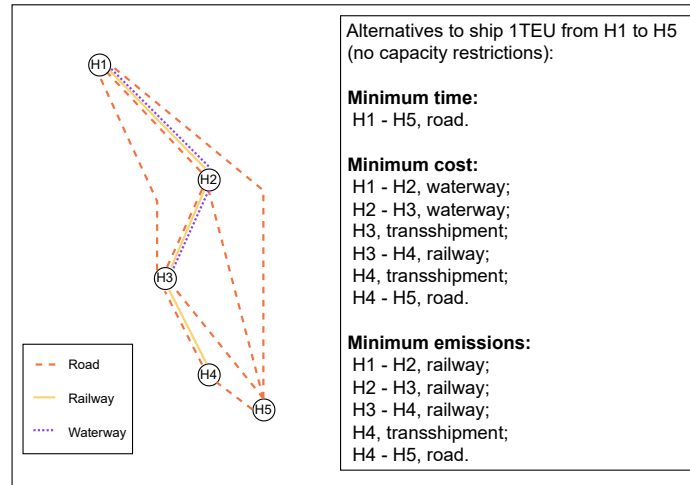


Figure 1: Route options for an intermodal network consisting of five hubs (H), connected by legs of three transportation modes.

Determining the transportation route for an order is not straightforward. On the one hand, it is easy to note from the figure that there are several possibilities to route an order through an intermodal transportation network with multiple hubs and legs. Typically, the time complexity of finding the optimal route under a given objective increases with the network size. For instance, under the commonly used Dijkstra shortest-path algorithm, the computational complexity grows with the number of hubs and legs in the network (Fredman & Tarjan 1987). On the other hand, we note two common operational complexities regarding railway and waterway transportation to be considered when planning and assigning orders to a transportation network. Firstly, railway and waterway transportation carriers are typically provided with strict service schedules according to which they may operate on any given leg. Such a schedule defines the time slots in which the given transportation service is available and may be selected in the transportation route. In contrast, a road network is typically quite extensive with flexible operations, so it may be assumed that road transportation is always available. Secondly, railway and waterway transportation requires a minimum shipment load size to make them economically viable due to fixed operating costs related to, for instance, using the infrastructure. Therefore, a transportation planner must incorporate the schedule and capacity requirements associated with railway and waterway transportation.

Besides the complexities of assigning one order to a route in an intermodal transportation network, LSP planners are typically tasked with assigning multiple incoming orders in any given time period. The planner then determines the transportation route for all the incoming orders, creating an opportunity to consolidate orders with specific characteristics, such as origin and destination. This allows planners to utilize transportation modes with minimum shipping volume requirements while improving economies of scale in cost and emissions. In addition, since the LSP planner arranges the consolidation of orders from various clients, it requires no direct cooperation between specific clients. But, optimizing the assignment and consolidation of such multiple orders to a transportation network can, in turn, be increasingly complex and time-consuming

(Van Heeswijk et al. 2018, Guo et al. 2020).

Finally, intermodal planning determines a fixed sequence of transportation legs and does not support a planner in deciding whether to reroute a shipment when a disruption is experienced on one or more of its legs. However, it is common for orders to experience delays along transportation legs en route, especially on railway and waterway services. Due to such a delay, the actual travel time of the leg may exceed its expected travel time. As a result of delays exceeding the expected travel time, orders may miss the service departure of the next transportation leg on the predetermined route and have to wait until the next service departs. At worst, such delays result in orders that arrive at their destination after their due date. The problem setting, therefore, concludes with the need to be able to react to travel time disruptions in transportation plans accordingly by replanning as best as possible given the order’s remaining delivery time via reactive synchronomodal planning.

4. Model description and solution approach

We develop a model that quantifies the impact of increasing railway and waterway transportation use on GHG emissions and costs. We achieve this by generating alternative transportation route options and providing relevant insights on the resulting trade-offs to a planner. In what follows, we describe the intuition behind our mathematical model. Specifically, we formulate the problem as a k -shortest path problem with order consolidation and time windows. To model reactive synchronomodal transportation planning using the shortest path formulation, we develop a multi-step solution approach consisting of two separate submodels. We refer to these as the offline intermodal and online (dynamic) synchronomodal modules. The intermodal module schedules all incoming orders, consolidating orders where possible. The synchronomodal module is only called when an in-transit shipment experiences a disruption. This module considers the real-time disruption updates of a given shipment to provide rerouting and, possibly, re-consolidation options. The online synchronomodal module, therefore, extends the offline intermodal module. We illustrate the process in Figure 2. Using this approach, we can greatly reduce the time complexity of the model. We relegate a comprehensive discussion of the model formulation to Appendix A.

Considering the complexities surrounding the joint optimization of route assignment and order consolidation of multiple orders in a transportation network, we make the following two design choices.

- *Dynamic planning.* To assign incoming orders to a transportation route, we propose a dynamic planning problem formulation. In such a formulation, orders are assigned on a first-come, first-served basis to transportation routes as the orders arrive over a rolling horizon. As a result, dynamic planning allows for fast customer response times regarding transportation options and costs.
- *Dynamic order consolidation.* We allow for dynamic order consolidation in which consolidation options are considered for an order as it arrives. Specifically, when a new order arrives, the algorithm checks for consolidation options for that new order with any existing, scheduled orders awaiting shipment. We

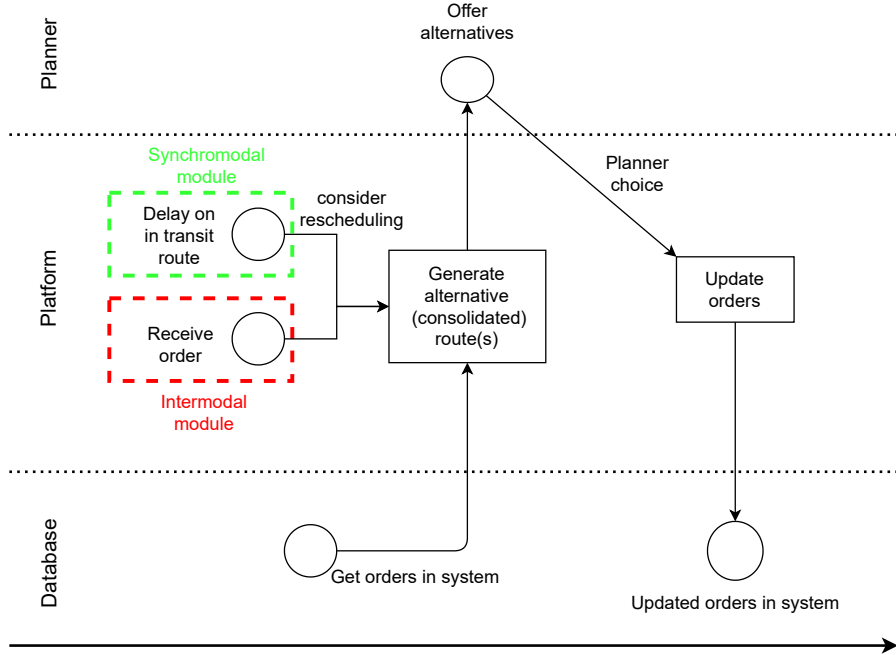


Figure 2: The working of our two-stage model approach.

do not allow for shipment splitting. Hence, we only allow for consolidation of orders with the same origin and destination and for which feasible solutions exist, defined as meeting the combined release and delivery dates. Such consolidation of orders with the same origin and destination ensures that the consolidated orders are treated as a single shipment for its entire route.

Additionally, consolidation is only allowed if the resulting order consolidation achieves economies of scale and reduces the system’s overall transportation costs. We note that an order’s assigned transportation route may only change if consolidated with a newly received order before it is released. Once an order is released, it is only available for re-consolidation in the synchronodal planning should a delay or disruption occur en route.

Using dynamic planning and consolidation, we propose a shortest-path approach to determine multiple route options from which the planner may choose one. The returned options vary according to their costs and emissions. For instance, if the “minimum-emissions” route is much more expensive than the “minimum-cost” route, the planner might hesitate to choose it. However, the planner might be willing to sacrifice some cost increase to obtain a meaningful reduction in GHG emissions. Our k -shortest path formulation provides a hybrid decision-making strategy by suggesting alternative transportation route options to the planner. In this strategy, we impose a cost bound on how much any individual order’s expected transportation cost may exceed that of the current minimum cost route. We express the cost bound as a maximum percentage cost increase over the minimum cost option. A set of minimum emissions routes up to a pre-specified number k , for which the transportation costs adhere to the imposed cost bound, are recommended to the planner. We refer to

this strategy as the *Bounded Cost* strategy. Using the Bounded Cost strategy, we can visualize the possible reduction in emissions achievable for a specific cost increase while respecting the imposed order delivery windows. The rationale behind providing alternative options is that it gives the planner a clear picture of the expected trade-off in overall costs, emissions, and travel time. The ultimate order-route assignment decision belongs to the planner and depends on the preference between cost and/or emissions.

Table 1: We generate transportation route options based on four minimization strategies.

Strategy	Objective
Unimodal Road Cost	Minimize transportation costs using unimodal road only
Cost	Minimize overall transportation costs
Emissions	Minimize overall transportation emissions
Bounded Cost	Minimize overall transportation emissions within predetermined cost-bound

As a result, we evaluate four intermodal minimization strategies using our model. We list the four strategies in Table 1. All strategies consolidate orders where possible. The *Unimodal Road Cost* strategy ships freight via road only. We include this strategy to visualize the negative effect of unimodal road transportation on emissions and costs compared to intermodal transportation. The *Cost* strategy determines the solution that minimizes overall transportation costs, consolidating orders where possible. For comparison purposes, we will evaluate the performance of each of the other three strategies with respect to this cost-minimizing transportation strategy. The *Emissions* strategy determines the solution that minimizes transportation emissions, consolidating orders where possible. In the *Bounded Cost* strategy, we determine several minimum emissions routes within the given cost bound. The cost bound is based on the minimum cost consolidation option if the order is consolidated and on the minimum cost non-consolidated option if order consolidation is not possible for the specific order.

Our synchronodal module extends the intermodal transportation planning algorithm by incorporating real-time travel duration and disruption information and provides the planner with alternative transportation solutions in response to route disruptions. Based on the travel time information, the synchronodal module presents the planner with a list of rerouting possibilities, who may then decide whether to reroute a given shipment. In doing so, it also provides new possibilities for order consolidation, which take the available real-time information into consideration while respecting an order’s due date, where possible. We illustrate the working of our proposed synchronodal transportation planning algorithm in Figure 3. We evaluate the same four strategies of Table 1 with the synchronodal module.

We use Dijkstra’s shortest path algorithm (Dijkstra 1959) to determine the minimum cost Unimodal Road, Cost, and Emissions solutions. We adapt the algorithm to return up to k , where k is pre-specified by the decision maker, alternative routes of increasing emissions for the Bounded Cost strategy. We note that alternative solution approaches, such as the ϵ -constraint used in Resat & Turkay (2019), may be applied

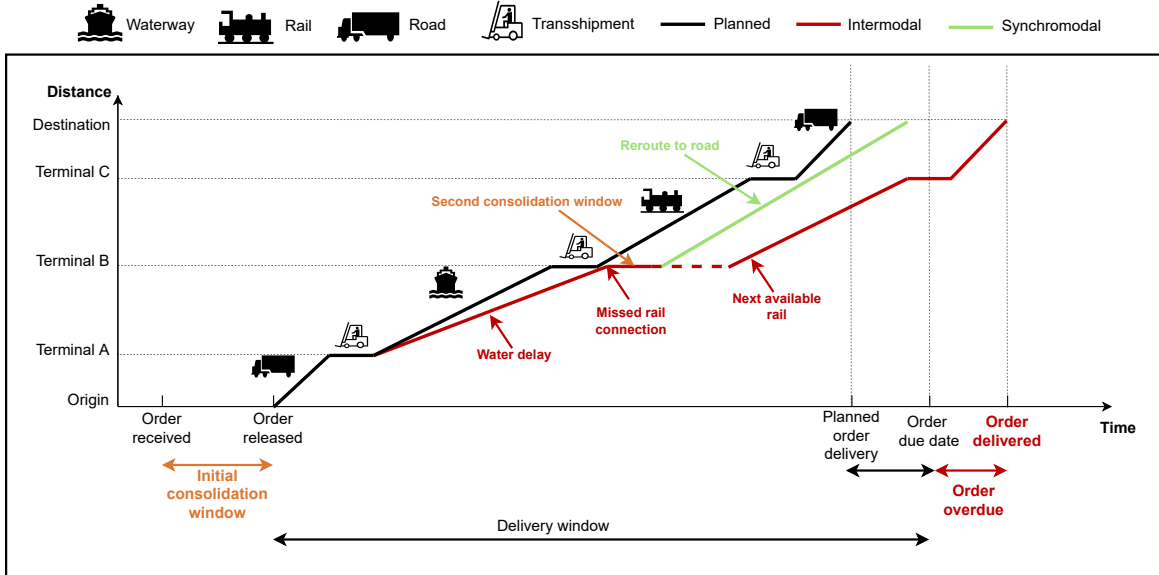


Figure 3: An illustration of the synchronomodal replanning module. An intermodal shipment is routed from origin to destination via Hubs A, B, and C. An unexpected delay between Hubs A and B results in a missed rail transportation leg at Hub B, risking an overdue delivery. Under intermodality, the shipment is stored at Hub B until the next available scheduled rail transportation. Under (reactive) synchronomodality, rerouting decisions that consider cost constraints may be made as soon as delays become known. Disruptions in the shipment travel time are therefore limited, improving transportation reliability.

instead to determine a Pareto frontier for the cost-emissions trade-off.

5. Experimental setup

We numerically demonstrate the working of the intermodal planning and synchronomodal replanning modules through a case study on a European multimodal network. In this section, we describe the numerical setup used in the analyses. While we report and discuss the results of this case study, we note that our model can be applied to any network setting and parameter configuration.

5.1. Intermodal planning based on expected travel times and order consolidation

Our numerical setup is inspired by our partner logistics service providers and information technology companies, responsible for shipping freight throughout Europe. We demonstrate the application of our model to a transportation network along the Rhine-Alpine corridor. As this is one of the busiest freight routes in Europe (European Commission n.d.b), it provides a representative case study to generate insights into the use of our model. The transportation network used is illustrated in Figure 4 and consists of a tri-modal corridor of road, railway, and inland waterway transportation with hubs in Rotterdam, Mannheim, Basel, Busto Arsizio and Milan. In Appendix B, we provide the distances related to the transportation legs in the network of Figure 4. Aside from that, we report the travel speed, cost, and emissions of the three transportation modes used in the network, where one can note that railway transportation generates less emissions but is more expensive than inland waterway transportation.



Figure 4: The representative intermodal transportation network considered in the numerical analyses.

In this transportation network, we assume that road transportation is always available. For railway and waterway transportation, we assume one shipment per day, departing respectively at 07:00 and 12:00, with a minimum order size restriction of two TEUs per shipment. Unless otherwise stated, we base all analyses on the same experimental setup, applying the mathematical model formulated in Appendix A in a simulation engine that generates orders to be shipped over the network of Figure 4.

Specifically, we simulate a rolling horizon, in which orders are scheduled as soon as the planner receives them. We let the length of the rolling horizon be five days. The origin, order size, release date, and arrival date are stochastic for each order. We let the destination for all orders be Milan; the origins may be either Rotterdam or Mannheim, with a possibility of zero and up to four orders originating from each origin per day. Each order's size can vary between one and four TEUs. The release date is the difference between receipt of the order and availability of the order for shipment. We let an order's release date vary between two and four days and let the order release time be 07:00. Recall that, for order consolidation, we only consider orders that have already been scheduled but have not yet been shipped. Hence, the longer the time to the release date of an order, the more time the planner has to consolidate the specific order with other shipments. The delivery window for each order varies between one and five days. In line with our model formulation of Appendix A, we apply a hard time constraint to delivery routes, such that a route may only be recommended to the planner if its expected delivery date falls within the provided delivery window. Our shortest choice in the delivery window of one day, therefore, ensures that, at least, unimodal road transportation is always a feasible transportation option. Likewise, allowing for a delivery window of five days ensures that the slowest transportation mode, waterway, is a feasible option for on-time deliveries. The delivery window is calculated as the difference between the order deadline and the release date. We provide the probability distributions for the origins, order sizes, time to release dates, and delivery windows in Table 2. We note that the order size of zero is included to allow for the possibility of receiving zero orders in a day. Once orders are received,

they are scheduled according to dynamic planning and consolidation, as elaborated in Section 4.

Table 2: The problem setup for our numerical analysis considers probability distributions for order size, origin, release date, and delivery window. RTM refers to Rotterdam, while MN refers to Mannheim.

Order Size (TEU)	0	1	2	3	4
Probability (RTM)	0.15	0.40	0.20	0.15	0.10
Probability (MN)	0.25	0.45	0.15	0.10	0.05
Time to Release Date (Days)	2	3	4		
Probability	0.10	0.30	0.60		
Delivery Window (Days)	1	2	3	4	5
Probability	0.10	0.10	0.20	0.20	0.40

5.2. Synchronodal re-planning based on real-time information

For our synchronodal replanning, we include stochastic travel times in the problem setup described in Section 5.1. Delays and disruptions are common in intermodal transportation. Transportation delays, modeled using stochastic travel times, can result in missed transportation connections and potential late deliveries that negatively impact transportation reliability. In addition to allowing for rescheduling of shipments in response to delays occurring en route, we also allow rescheduling shipments in response to early arrivals at intermediate hubs. Early arrivals, while less prominent, can potentially enable a more sustainable transportation connection that was previously unfeasible. We model stochastic travel times using different probability distributions for each transportation mode. For road, we use a shifted binomial distribution, $B(n, 0.15) + n$, where n is the minimum travel time for each leg, determined by the maximum average speed of 70km/h (Yee et al. 2021, Demir et al. 2017, Chiang & Roberts 1980, Ambra et al. 2019a). Railway transportation times are based on Barta et al. (2012), using an average speed of 30 km/h. Finally, we assume a uniform distribution for waterway transportation between 9 and 11 km/h (Yee et al. 2021, Marine Traffic 2020, Demir et al. 2017).

The value of synchronodality lies in its ability to replan an order’s scheduled route in response to stochastic travel time realizations. However, the extent of the value is dependent on the availability of alternative transportation options in case of missed connections and the time remaining in an order’s delivery window. While our synchronodal module can re-plan shipments for several orders at a time, we focus on the synchronodal re-planning of a single order in this adapted problem setup with stochastic travel times. Following the movement and replanning of a single order through the transportation network over the rolling horizon allows us to isolate and analyze the effect of consolidation, possible re-consolidation during re-planning, and varying delivery windows for this order’s re-planning. We refer to this order as Order X to avoid confusion with other orders. We fix the origin and destination of Order X as Rotterdam and Milan, respectively. As Order X is shipped through the network, its route may be updated according to its realized travel times,

including possible consolidation with new orders, using the synchromodal module. The result is a multi-order analysis, considered over a rolling horizon, with order consolidation and stochastic travel times.

Since the minimum order size requirement for railway and waterway is set to two TEU in the analysis, we set Order X 's order size to one TEU. This choice in order size allows us to investigate the effect of consolidation on route choice when an order's size is less than the minimum load requirement for railway and waterway. To evaluate transportation rescheduling and re-consolidation opportunities for Order X , we include the possibility for orders to originate at Basel, in addition to those at Rotterdam and Mannheim. Up to four orders may arrive at each hub each day. To evaluate consolidation opportunities for Order X with other orders in the network, we extend the time to release dates and delivery windows for incoming orders. The updated problem setup and probability distributions are provided in Table 3.

Table 3: The problem setup for the synchromodal numerical analysis of Section 6.2. RTM refers to Rotterdam, MN to Mannheim, and BA to Basel.

Order Size (TEU)	0	1	2	3	4
Probability (RTM)	0.15	0.40	0.20	0.15	0.10
Probability (MN)	0.25	0.45	0.15	0.10	0.05
Probability (BA)	0.05	0.40	0.30	0.15	0.10
Time to Release Date (Days)	4	5	6	7	8
Probability (RTM + MN)	0.10	0.30	0.60	0.00	0.00
Probability (BA)	0.00	0.10	0.10	0.30	0.50
Delivery Window (Days)	4	5	6	7	8
Probability (RTM + MN + BA)	0.05	0.05	0.20	0.25	0.45

We note that the time to release dates and delivery windows in Table 3 refer to that of all the orders, excluding Order X , received during the time period considered in the rolling horizon. For Order X , we set the time to release date as one week. To evaluate the effect of longer delivery windows, we vary Order X 's delivery window between one and eight days.

6. Results and discussion

This section describes the results of applying the inter- and synchromodal planning tools. We first describe the value of providing alternative intermodal transportation solutions, beyond the minimal costs and/or emissions solutions, with the possibility of order consolidation. We then discuss the effect on relevant costs and emissions when using synchromodality to react to disruptions or delays en route. Synchromodal transportation may lead to an increase in both transportation cost and emissions relative to fixed intermodal transportation for short delivery windows in which road transportation tends to be the only viable option to

ensure timely delivery. To justify this dual increase, we also discuss the increased reliability of synchronomodal transportation over intermodal transportation regarding on-time shipments, given disruptions or delays en route. The analyses illustrate how our model may be incorporated into a digital control tower, bringing transparency to the cost-emissions trade-offs in intermodal (re-)planning.

6.1. Intermodal planning based on expected travel times and order consolidation

We perform 10 simulation runs for each of the strategies considered for the problem setup described in Section 5.1 to account for the stochasticity in order arrivals, variation in order size, and possible origin over the rolling horizon. To ensure a fair comparison of the results obtained over the various strategies, we use the same simulated sample path in the simulation runs for each strategy.

The results for the Bounded Cost strategy from the rolling horizon simulation, with respect to the Cost strategy and averaged over the multiple simulation runs, are shown in Table 4. We report the cost-emissions trade-offs for a cost bound ranging from 5% to 50%. The average expected change in total costs and emissions over all orders received by the end of the rolling horizon is shown in, respectively, the Cost and Emissions column. The Max Cost and Min Cost (resp. Emissions) represent the maximum and minimum change in costs (emissions) observed with respect to the intermodal Cost strategy for each cost bound over the instances considered. The cost bound is applied to each individual order. As an example, it may be seen in Table 4 that, for a cost bound of 30% per order or higher, the expected cost increase for the instances considered is limited to approximately 4% across all orders and the maximum expected cost increase to approximately 6%. Concurrently, the expected emissions reduction is almost 5% across all orders, with reductions up to 11%. We note it is possible that, for some orders, alternative route options, regardless of increasing the cost bound, may not exist. As a result, the cost and emissions for those limited instances remain unchanged as the cost bound increases, indicated by a 0% change in the Minimum Cost/Emissions column. The standard deviation of Table 4 represents the cost and emissions variations obtained over the instances considered.

The last column of Table 4 reveals how the cost per kilogram of reduced carbon emissions increases with higher cost bounds. Such an increase may seem counter-intuitive. However, since the Cost strategy is an intermodal strategy that already uses low-cost transportation modes, it utilizes waterways and railways where possible. As the cost bound increases, changes in the recommended transportation routes are generally limited to replacing waterway transportation with railway transportation (railway being more expensive and environmentally friendly than waterway transportation, see Table 10). In our experimental setup, shifting from waterway to railway transportation reduces the emissions by approximately 40% per TEU-km (see Table 10) but increases the related transportation cost by approximately 160% per TEU-km. This results in a higher cost per kilogram of reduced emissions. We note, however, that this result depends on the specific cost-emissions trade-offs of the transportation modes considered. Furthermore, it is sobering to note that the cost of emissions reductions, as estimated in this work and comparable to other such efforts, is typically much higher than the cost of emissions offsetting. Emissions offsetting should be a last resort for unavoidable emissions and is made possible through mechanisms such as the European Trading System

(European Commission n.d.a). We note that the cost to offset a tonne of carbon dioxide produced was as low as €50.54 at the time of writing (EMBER 2024).

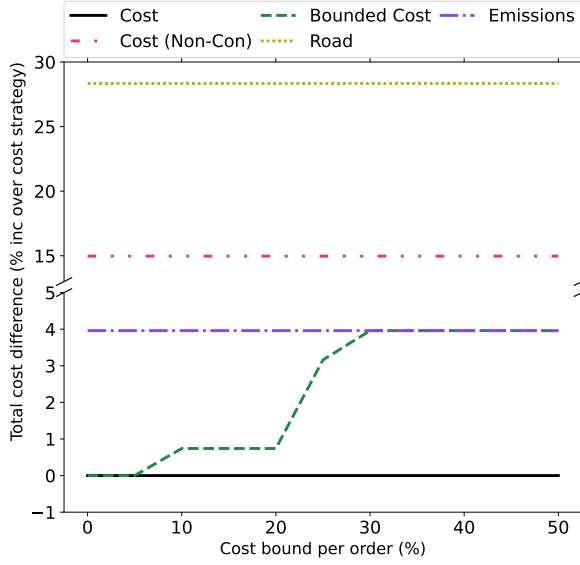
Table 4: The results obtained from our simulation analysis when following the Bounded Cost strategy for a cost bound up to 50%. Cost and emissions (Em), expressed as a percentage (%), are determined as the expected increase with respect to the Cost strategy. The cost per kilogram of reduced emissions, expressed in Euro per kilogram of CO₂ equivalent (€/kg CO₂-eq), is also determined with respect to the Cost strategy.

Bound (%)	Cost (%)	Max Cost (%)	Min Cost (%)	Std Dev	Em (%)	Max Em (%)	Min Em (%)	Std Dev	€/kg CO ₂ -eq
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.74	3.41	0.00	1.04	-1.15	0.00	-4.58	1.57	1.98
15	0.74	3.41	0.00	1.04	-1.15	0.00	-4.58	1.57	1.98
20	0.74	3.41	0.00	1.04	-1.15	0.00	-4.58	1.57	1.98
25	3.16	5.19	0.00	1.85	-4.09	0.00	-11.07	3.34	3.10
30	3.96	5.97	0.00	1.95	-4.85	0.00	-11.07	3.08	3.27
35	3.96	5.97	0.00	1.95	-4.85	0.00	-11.07	3.08	3.27
40	3.96	5.97	0.00	1.95	-4.85	0.00	-11.07	3.08	3.27
45	3.96	5.97	0.00	1.95	-4.85	0.00	-11.07	3.08	3.27
50	3.96	5.97	0.00	1.95	-4.85	0.00	-11.07	3.08	3.27

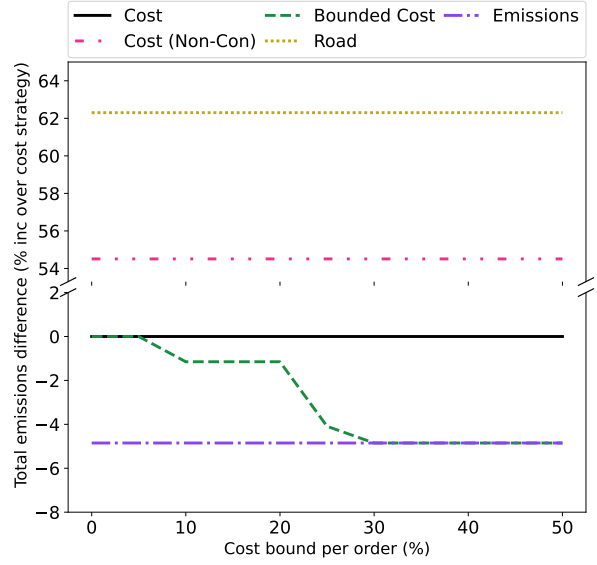
We visualize the effect of increasing the cost bound on the total expected costs and emissions using the Bounded Cost strategy in Figure 5. For comparison purposes, we additionally visualize the cost incurred and emissions released via both the Unimodal Road Only strategy and the Cost strategy when consolidation is not allowed (Non-Con) in Figure 5. In doing so, we highlight the considerable positive impact of, firstly, a modal shift from unimodal road to intermodal transportation and, secondly, intermodal consolidation strategies on both costs and emissions.

From Figure 5, it may be seen that the Bounded Cost strategy is bounded by the Cost strategy from below (above) and the Emissions strategy from above (below) in terms of costs only (emissions only). As the cost bound increases above 30% and the cost no longer constraints the minimal emissions transportation route option, the Bounded Cost strategy reduces to the Emissions strategy. Table 4 and Figure 5 further highlight how a relatively high cost bound, up to 20% per order, only increases the total expected costs (when following the Cost strategy) by less than 1%, and improves emissions by almost 2%.

We show the modal split, as the cost bound is increased for the Bounded Cost strategy, in Table 5. We can see that the Cost strategy when the cost bound is 0% results in an average modal share of approximately 12% road, 72% railway, and 16% waterway transportation. As the cost bound increases, railway transportation’s share gradually increases to 86%, while waterway reduces to less than 2%. From the problem setup and Table 10, we have that railway transportation is more expensive than waterway transportation. At the same time, railway transportation is less carbon-intensive than waterway transportation. As a result, the



(a) Increase in overall expected costs as the cost bound per order is relaxed.



(b) Reduction in overall expected emissions as the cost bound per order is relaxed.

Figure 5: For the numerical instances considered, the Bounded Cost strategy leads to an average maximum total expected cost increase of less than 4% compared to the Cost strategy and can improve emissions by up to almost 5%. Allowing for order consolidation leads to both cost and emissions savings.

share of railway transportation gradually increases as the cost bound increases. Road transportation, largely representing the last mile deliveries, remains constant at around 12%

6.2. Sychromodal re-planning based on real-time information

Given that orders are associated with fixed delivery windows, any delays experienced while in transit may result in late deliveries. The sychromodal replanning module may respond to such delays by proposing an alternative route to ensure timely delivery. Evidently, the shorter an order’s delivery window, the higher the potential impact of a delay on that order’s on-time delivery. Consider, for instance, the transportation options in our numerical analysis example. In this example, an order’s pre-specified delivery window may restrict the feasible transportation options available to a planner to ensure on-time delivery. Specifically, any order with a delivery window of one day can only be shipped by unimodal road transportation to ensure on-time delivery. Railway transportation becomes feasible between some intermediate hubs for a delivery window of two or more days. Finally, for a delivery window of three days or more, waterway transportation becomes feasible between some of the intermediate hubs. To prevent late deliveries, especially for shorter delivery windows, sychromodal re-planning generates alternative route options, which often, but not always, include the faster, yet more expensive and less sustainable, road transportation.

We, therefore, evaluate the effect of sychromodal replanning for different time windows, when compared to planned intermodal transportation options, on reliability, cost and emissions. For comparison purposes, we perform 100 simulation runs for the Cost and Emissions strategies. We do not consider the Bounded

Table 5: As the cost bound increases, the average share of road transportation remains more or less constant, while the share of the cheaper but less sustainable waterway transportation is exchanged for the more expensive but more sustainable railway transportation.

Bound (%)	Road (%)	Railway (%)	Waterway (%)
0	12.10	71.63	16.27
5	12.10	71.63	16.27
10	12.09	75.05	12.86
15	12.09	75.05	12.86
20	12.09	75.05	12.86
25	12.13	82.78	5.09
30	12.12	86.19	1.69
35	12.12	86.19	1.69
40	12.12	86.19	1.69
45	12.12	86.19	1.69
50	12.12	86.19	1.69

Cost strategy and instead focus on the value of synchronomodal replanning, as we know from Figure 5b that the results of the Bounded Cost strategy will fall within that of the Cost and Emissions strategies. For a delivery window of one day, we know that only road transportation is feasible. Hence, both intermodal and synchronomodal transportation results in the same solution, with on-time delivery, such that a delivery window of one day is not included in the analysis.

For each instance in which the fixed intermodal strategy results in late deliveries, the synchronomodal option can deliver 100% on time at a trade-off of higher unit costs and emissions. In Table 6, we therefore only show the reliability that results from following a fixed intermodal strategy. We define reliability by the percentage of on-time deliveries and the hours of late delivery when a shipment is overdue. Intermodal transportation reliability can be as low as having only 84% of on-time delivery, with an average late delivery of 15.25 hours. For the instances considered, the reliability of intermodal transportation generally increases as the delivery window increases. The slight drop in the on-time delivery between delivery windows two and three is attributable to the increase in the share of rail and waterway transportation. This increase results in longer travel times and thereby an increased likelihood of late deliveries. While delays occur slightly more often with delivery windows of three and four days, the severity in terms of hours overdue when late improves when compared to a delivery window of only two days. We note that the results also depend on the consolidation options with other orders in the system.

The synchronomodal reliability guarantee is largely brought about by switching to faster road transportation, but often also replacing waterway transportation with a combination of railway and road transportation. We

Table 6: The percentage of on-time deliveries achieved by the fixed intermodal transportation policy for each of the minimum strategies considered. In parentheses, we show the average time, in hours, that a shipment is delivered late when it is overdue.

Delivery Window	2	3	4	5	6	7
Cost Strategy	90% (18hrs)	84% (15.25hrs)	84% (15.25hrs)	100% (0hrs)	100% (0hrs)	100% (0hrs)
Emissions Strategy	90% (18hrs)	88% (15.25hrs)	88% (15.25hrs)	100% (0hrs)	100% (0hrs)	100% (0hrs)

show this expected change in costs and emissions in Table 7. The results indicate that for a delivery window from 2 to 4 days, synchromodal replanning avoids late delivery at the expense of slightly higher costs and emissions. Longer delivery windows do not require synchromodal replanning for timely delivery under the Cost or Emissions strategy so that cost and emissions remain unchanged.

Table 7: The expected increase in costs and emissions for the synchromodal option, relative to the intermodal option, for different delivery windows. The results are expressed as the increase in cost (%) and emissions (%).

Delivery window		2	3	4	5	6	7
Cost Strategy	Cost increase	0.35%	0.89%	0.89%	0.00%	0.00%	0.00%
	Emissions increase	2.25%	13.84%	13.84%	0.00%	0.00%	0.00%
Emissions Strategy	Cost increase	0.35%	2.17%	2.17%	0.00%	0.00%	0.00%
	Emissions increase	2.25%	7.44%	7.44%	0.00%	0.00%	0.00%

We highlight that, despite the costs and emissions increase in synchromodality, both costs and emissions are still significantly less than that of Unimodal Road transportation. We further note that we only compare the transportation costs of the synchromodal and intermodal planning strategies. We do not impose a penalty fee for late deliveries in the case of intermodal planning. Should such a penalty be imposed, synchromodality may be cost-favorable compared to intermodal planning, as investigated, for instance, in (Yee et al. 2021).

7. Conclusions and managerial relevance

Our paper addresses the need to incorporate sustainability and ESG criteria into managerial decision-making. Specifically, we bring transparency to the costs and emissions of intermodal freight transportation through a multiple shortest-path model that identifies intermodal transportation routes considering order consolidation and time windows imposed by intermodal transportation schedules.

Using our multiple shortest path model, we propose a Bounded Cost approach to minimize transportation emissions while ensuring that each individual order is routed within a predetermined cost limit. Using this Bounded Cost strategy, we visualize route options of decreasing emissions at an increasing cost. We apply the model to a representative intermodal transportation network. For the instances considered, total emissions

are minimized when the cost bound is chosen as at most 30% per shipment above the minimum cost route option. While the bound is high for individual orders, it results in less than a 4% increase in overall expected total transportation costs—and up to 6%—compared to the total costs obtained when always choosing the minimum cost route option per order. In addition, total expected emissions can be further reduced by almost 6% on average, and up to 11%. Our Bounded Cost strategy may be more relevant for transportation planners than the pure emission-minimizing objective generally proposed in the literature.

In addition, using synchronomodality, we allow for real-time rescheduling and consolidation of planned shipments when disruptions are experienced en route. As a result, synchronomodal replanning can avoid late deliveries, generally at slightly higher costs and emissions. The model may be seen as a step towards improving the sustainability of freight transportation and may easily be incorporated into current transportation planning tools.

We model synchronomodality from the perspective of an LSP transportation planner with full visibility regarding the different transportation modes available to the planner. We highlight, however, that successful synchronomodal operations require integration and collaboration between all stakeholders in a transportation network, as assumed in our model, which may not always be the case in reality.

Under the Non-Financial Reporting Directive (NFRD), all large companies and all listed companies in the European Union must disclose information on the impact of their activities on people and the environment. This European legislation pushes the entire market towards greening and transparency. For many businesses, Scope 3 emissions account for a significant share of their carbon footprint. The GHG emissions from outsourced logistics and freight transportation fall under Scope 3. Our models can be used to create visibility of the environmental impact of freight transportation and provide insight into the cost-emissions trade-offs of more carbon-friendly alternative solutions. Making these trade-offs more transparent may facilitate the adoption of alternative transportation solutions other than the cost-minimizing solution, as it shows how much emissions can be saved at which cost. Transportation planners can adopt these alternative routes to reduce emissions or even propose that their customers pay for them. With the new legislation to report (and reduce) their carbon footprint, many logistics companies have deviated from their original cost-only focus that dominated the logistics industry until recently in favor of better environmental performance.

In future work, our model may be extended to a flow-based or routing model for intermodal and synchronomodal transportation planning (Hrušovský et al. 2021, Zhang et al. 2022). When determining route options, we now only consider those where the expected travel time is within the order’s provided delivery window. However, adhering to these delivery windows may be impossible when delays occur en route. In such a case, the synchronomodal module will default to the fastest route, typically, but not always, road transportation. This delivery window constraint may limit the synchronomodal transportation options available to the planner. In addition, clients may tolerate accepting late deliveries in case of disruptions. The model may be extended in future work by relaxing the delivery window constraint, such as introducing a penalty for late deliveries. Future work may also extend our model to consider static forms of order consolidation.

8. Data statement

The data underlying this paper are available in the paper and its appendices.

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Appendices

A. Model formulation

In this section, we formulate the mathematical model underlying the intermodal and synchromodal modules in the platform. We provide a list of frequently used notations in Table 8.

To formulate the problem, we represent the known transportation network using a bi-directional graph, $G = (V, A)$, where the set of vertices, V , denotes the network hubs and the set of arcs, A , denotes the various network legs. To account for transshipment between modes in the graph, we create separate nodes for each transportation mode available at a hub. The result is that each arc is associated with one transportation mode only. Recall that an order’s origin (r) and destination (s) is also classified as a hub ($r, s \in V$). A route consists of a number of arcs (legs) connected by nodes (hub). Should a transportation link exist between

Table 8: The list of frequently used notation abbreviations.

Symbol	Meaning	Symbol	Meaning
H_i	Hub i	(i, j)	Arc connecting node i with node j
$G = (V, A)$	Graph G with node set V and arc set A	\mathcal{L}	Delivery window
P_{ij}	Path from node i to node j	$c(P_{ij})$	Performance vector associated with path P_{ij}
\mathcal{F}	The total number of feasible paths for a given order	b_{ij}	Minimum load size associated with arc (i, j)
Ω	Set of total orders in the system at a given time	Ω_W	Set of scheduled orders waiting for departure
Ω_N	Set of received orders not yet scheduled	Ω_T	Set of in-transit orders
m_c	Maximum cost bound	m^e	Minimum emissions bound
c_{ij}^{cost}	Cost incurred to ship one freight unit from node i to node j		
c_{ij}^{em}	Emissions incurred to ship one freight unit from node i to node j		
u_{ij}^a	Daily expected arrival time of transportation mode at node j from node i		
u_{ij}^d	Daily expected departure time of transportation mode from node i destined for node j		
w_{ij}	Expected waiting time at node i scheduled to depart for node j		

nodes i and j , they are said to be connected. We denote the resulting arc by (i, j) . We visualize such a graph formulation in Figure 6.

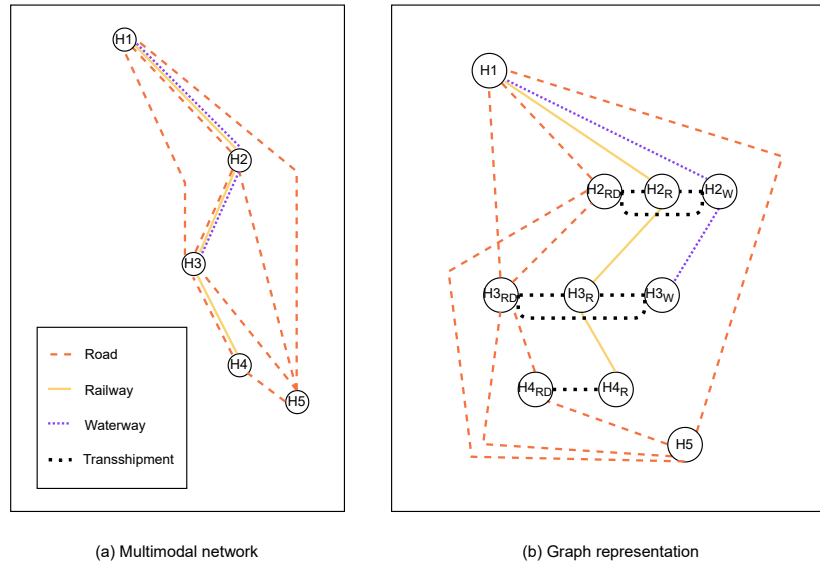


Figure 6: The multimodal network of Figure 1, reproduced in (a), can be converted to a graph, as shown in (b), in which each node for hubs H2 - H4 represent either road (RD), railway (R) and waterway (W) transportation. Transshipment arcs connect different transportation nodes at a hub, should different transportation modes be supported by the specific hub.

In the following sections, we first discuss the shortest path model formulation. We treat this formulation as

our base model for determining each of the different shortest paths, namely minimizing expected (unimodal road) costs and emissions. To extend the base model to intermodal transportation, we include minimum load requirements, scheduling restrictions and time windows to meet delivery deadlines, in addition to order consolidation. Finally, we extend the model to determine up to a set number, k , of alternative minimum emissions routes in ascending order of emissions.

A.1. The shortest path model formulation

Consider the representation of the transportation network as a bi-directional graph, $G = (V, A)$. In graph $G = (V, A)$, each arc $(i, j) \in A$ is associated with a performance criteria vector, $c_{ij} = (c_{ij}^{cost}, c_{ij}^{em})$, representing the objectives to be optimized. We let em represent emissions for brevity purposes. Recall that each arc (i, j) has a specific transportation mode associated with it. It follows that c_{ij}^{cost} and c_{ij}^{em} respectively denotes the expected transportation costs per unit transported over arc (i, j) and its associated emissions given the known transportation mode of the arc. A path P_{ri} from the origin r to a node i is a sequence of nodes (and arcs) $P_{ri} = (r \equiv n_1, \dots, n_h \equiv i)$ of length $h \geq 2$, where each arc $(n_z, n_{z+1}) \in A$ for $z = 1, \dots, h - 1$. Path P_{ri} is evaluated by means of its performance vector $c(P_{ri}) = (c^{cost}(P_{ri}), c^{em}(P_{ri}))$ where

$$c^l(P_{ri}) = \sum_{(p,q) \in P_{ri}} c_{pq}^l, \quad (1)$$

for $l = cost, em$. For a given order, we let $x_{ij} = 1$ if arc (i, j) is in a feasible path and 0 otherwise. The general objective is to determine the minimum path in G from a specific origin node $r \in V$ to a specific destination node $s \in V$ that minimizes the given performance criteria. For each l , we have

$$\min f^l(x) = \sum_{(i,j) \in A} c_{ij}^l x_{ij} \quad (2)$$

subject to

$$\sum_{j:(i,j) \in A} x_{ij} - \sum_{j:(j,i) \in A} x_{ji} = 1 \quad \text{if } i = r \quad (3)$$

$$\sum_{j:(i,j) \in A} x_{ij} - \sum_{j:(j,i) \in A} x_{ji} = 0 \quad \forall i \in V \setminus \{r, s\} \quad (4)$$

$$\sum_{j:(i,j) \in A} x_{ij} - \sum_{j:(j,i) \in A} x_{ji} = -1 \quad \text{if } i = s \quad (5)$$

$$x_{ij} \geq 0 \quad \forall (i, j) \in A. \quad (6)$$

In line with literature (see for example Taccari (2016)), Constraint (3) ensures that the solution path starts at origin node r . Constraint (4) ensures that, for every node visited, except for the origin and destination nodes r and s , there is both an entry and an exit arc. Constraint (5) ensures that the solution path terminates at destination node s . Constraint (6) ensures that the variables are non-negative.

The different formulations for each of the performance criteria essentially differ in the form of a different objective function and (possibly) additional constraints. In the subsections that follow, we build on the unimodal road base shortest path model to include the main transportation constraints specific to our model.

A.2. Transportation planning requirements and constraints

We extend the shortest path formulation of Section A.1 for intermodal transportation by including three main constraint sets, namely capacity requirements, scheduling restrictions and time windows.

Minimum load requirements. Recall that both rail and water transportation typically impose minimum shipment load sizes. As a result, the shortest path solution may only traverse arc (i, j) should the load size, B_ω , of the given order ω meet the minimum load requirements of the specific transportation mode associated with arc (i, j) .

We define b_{ij} as the minimum load size associated with arc (i, j) . We model the restriction as

$$B_\omega \geq b_{ij}x_{ij} \quad \forall (i, j) \in A, \quad (7)$$

where Constraint (7) ensures the minimum order load requirements associated with arc (i, j) are respected.

Schedule restrictions. We impose schedule constraints on both rail and waterway transportation. We do not impose schedule constraints on road transportation and further assume that transshipment is always available. To model schedule constraints, we let, u_{ij}^d and u_{ij}^a , respectively, be the daily planned departure and arrival times of the transportation mode departing node i and arriving at node j . We denote the expected travel time between node i and j as t_{ij} .

As a result of the fixed schedules of some transportation modes, waiting times are incurred whenever an in-transit order is left idle at a node, i.e., in temporary storage or in expectation of a scheduled rail or waterway transportation departure. We note that, for modeling purposes, temporary storage at hubs is assumed to be free of charge.

We let τ be the release time of the order and M a sufficiently large number. If the waiting time between two transportation services is at most 24 hours, as in our case, M can be set to 24. We calculate the waiting time of a given order, w_{ij} , at node i for transportation on arc (i, j) , as

$$w_{ij} = (u_{ij}^d - \tau)x_{ij} \quad \forall (i, j) \in A, i = r \quad (8)$$

$$w_{ij} \geq u_{ij}^d x_{ij} - \sum_{\{z:(z,i) \in A\}} u_{zi}^a x_{zi} \quad \forall (i, j) \in A, i \neq r \quad (9)$$

$$w_{ij} \leq u_{ij}^d x_{ij} - \sum_{\{z:(z,i) \in A\}} u_{zi}^a x_{zi} + M(1 - x_{ij}) \quad \forall (i, j) \in A, i \neq r \quad (10)$$

$$w_{ij} \geq 0 \quad \forall (i, j) \in A, i \neq r \quad (11)$$

$$w_{ij} \leq Mx_{ij} \quad \forall (i, j) \in A, i \neq r. \quad (12)$$

This set of equations ensures that a non-negative waiting time is associated with every arc (i, j) that is used in the path, and that the waiting time is equal to zero otherwise. We sum over the arriving arcs since only one may equal one.

Time windows. Each order received by the LSP planner has an associated release and due date. These dates refer to the order’s delivery window, \mathcal{L} , during which the order should be shipped from its origin to destination. Path P_{rs} is therefore only considered to be a feasible path between origin r and destination s if its combined expected travel and waiting times are within the order’s delivery window \mathcal{L} . We model the time window constraints as

$$\sum_{\{i:(i,j) \in A\}} \sum_{\{j:(i,j) \in A\}} (w_{ij} + t_{ij})x_{ij} \leq \mathcal{L}, \quad (13)$$

where Constraint (13) guarantees that arc (i, j) may only be included in the shortest path if its inclusion respects the given order’s delivery window.

A.3. Order consolidation

The system state consists of all orders waiting to be scheduled, those already scheduled and waiting for shipment, and those in-transit. Let Ω be the set of total orders in the system at time t . We have that $\Omega = \Omega_N \cup \Omega_W \cup \Omega_T$, where Ω_N is the set of all orders which have been received from clients and have yet to be scheduled for transportation by the planner. Order assignment is made periodically. Between successive assignment periods, incoming orders are added to the set Ω_N . At each assignment period, orders from the set Ω_N are scheduled on a first-come, first-served basis until $\Omega_N = \emptyset$. We denote Ω_W as the set of scheduled orders that are awaiting to be shipped, i.e., the received orders that have been scheduled for shipment by the LSP planner, but which have not yet been released for said shipment. The orders in Ω_N , being considered by the LSP planner for scheduling, may be consolidated for shipment with any order in Ω_W , which has already been scheduled but is still awaiting shipment. After scheduling the new order, it is added to the set Ω_W , and removed from the set Ω_N . As soon as an order is released for shipment, it is moved from set Ω_W to the in-transit set Ω_T and is no longer available for consolidation with newly arriving orders.

To avoid splitting a shipment in transit, only orders that share both the origin and destination node are considered for consolidation. Should such order pairs exist, a so-called *dummy* order is created. The characteristics of such a dummy order constitute that of its sub-orders. Specifically, the dummy order’s size is the sum of its sub-orders’ sizes, while its release and due dates are, respectively, the latest and earliest of each of its sub-orders. The shortest path model formulation may then be applied using the dummy order.

We note that consolidated orders may be more expensive per unit shipped compared to the unit cost of the pre-consolidated orders. Our use of unit cost refers to the expected cost of a shipment per unit shipped (TEU in our case) compared to the total size of the given shipment. A possible reason for such an occurrence is when the delivery window of one consolidated order is reduced to adhere to a shorter delivery window of another order in the consolidation. As a result, waterway or rail transportation, which may have resulted in lower unit costs for an order pre-consolidation, may no longer be a feasible option for on-time delivery. We therefore include an additional cost-based rule when allowing for order consolidation. Let order $\omega_n \in \Omega_N$ be identified for consolidation with order $\omega_w \in \Omega_W$. For each order, we let the pre-consolidated unit cost be

$U_{\omega_n}^{cost}$ and $U_{\omega_w}^{cost}$, respectively. The unit cost for, say order ω_n , can be calculated as

$$U_{\omega_n}^{cost} = \sum_{(i,j) \in A} \frac{c_{ij}^{cost} x_{ij}}{B_{\omega_n}}.$$

Given the unit cost $U_{\omega_{nw}}^{cost}$ of the resulting consolidated dummy order, say ω_{nw} , we impose the cost-based rules

$$U_{\omega_{nw}}^{cost} \leq U_{\omega_n}^{cost} \quad (14)$$

$$U_{\omega_{nw}}^{cost} \leq U_{\omega_w}^{cost} \quad (15)$$

to ensure that the resulting consolidated unit costs do not exceed that of the pre-consolidated orders.

A.4. The k -shortest path model formulation

The shortest path problem formulation is further extended to a k -shortest path problem to visualize the trade-off between expected costs and emissions for different orders and transportation options. We model the k -shortest path problem for performance criteria $l = em$. To determine the set of alternative minimum emissions routes, k , in ascending order of emissions, we let \mathcal{F} be the total number of feasible paths for a given order.

For $k \leq \mathcal{F}$, we can now iteratively solve for the shortest path until the k shortest paths are obtained. Otherwise, all the feasible shortest paths are returned. For $y \in \mathcal{Y} = \{1, 2, \dots\}$ where $|y| = \min\{k, \mathcal{F}\}$, the objective function of each shortest path $y \in \mathcal{Y}$ is calculated using the formulation and relevant restrictions and constraints of Sections A.1, A.2 and A.3, such that the problem becomes

$$\min f_y^{em}(x) = \sum_{(i,j) \in A} c_{ij}^{em} x_{ij}. \quad (16)$$

We define a feasible path in the set k using three additional constraints, namely cost, transshipment, and unique path constraints.

Cost constraints. An emissions route is only considered as a feasible path and, therefore, eligible for inclusion in the set k if its total transportation costs are at most equal to the costs of the minimum unimodal road transportation path. The driving reason for this rule is that since road transportation is currently the most flexible and reliable form of freight transportation, any route with a cost higher than unimodal road transportation will likely be disregarded by a planner. We additionally include this rule to encourage the adoption of more sustainable transportation modes by visualizing both the cost and emissions benefit thereof, when available, over unimodal road transportation. We let the cost associated with the minimum unimodal road path be m^{cost} , referring to m^{cost} as the maximum allowable emissions path cost. The resulting cost-based rule

$$\sum_{(i,j) \in A} c_{ij}^{cost} x_{ij} \leq m^{cost} \quad (17)$$

ensures that the cost associated with the returned emissions path y is, at most, that of the unimodal road transportation path.

Transshipment constraints. When determining the k -shortest paths, the model may recommend several paths with multiple transshipments at a hub as different shortest paths. It may, therefore, result in recommending multiple paths consisting of the same transportation services (hub, mode, and time) but only differing in the number of transshipments at a specific hub(s). To avoid such back-and-forth consecutive transshipments at any given hub, we allow for a maximum of one transshipment between transportation legs.

We ensure that no two consecutive transshipment arcs may be considered in a feasible emissions path using the following constraint

$$x_{ij} + x_{jz} \leq 1 \quad \forall (i, j), (j, z) \in A^{ts}, \quad (18)$$

where A^{ts} refers to the set of arcs whose transportation mode is transshipment.

Unique shortest path constraints. To obtain up to k unique shortest paths (of increasing emissions), we include a minimum allowable emissions constraint. We use m^{em} to denote a path's minimum allowable emissions and initialize $m_y^{em} = 0$ for $y = 1$. For $y > 1$, we let $m_y^{em} = f_{y-1}^l(x)$. The constraint

$$\sum_{(i,j) \in A} c_{ij}^{em} x_{ij} > m_y^{em}, \quad (19)$$

ensures that the emissions restrictions are adhered to for each path, such that up to k unique shortest emissions paths are returned.

B. Network and problem parameters

The distances used in our numerical analysis are shown in Table 9, as derived from (Yee et al. 2021, European Commission 2020, Bureau Voorlichting Binnenvaart 2020).

Table 9: The distances used in the numerical analysis, expressed in kilometers.

Leg	Road	Railway	Waterway
Rotterdam → Mannheim	560	570	600
Rotterdam → Basel	770		
Rotterdam → Milan	1190		
Mannheim → Basel	280	270	260
Mannheim → Milan	630		
Basel → Busto Arsizio		360	
Basel → Milan	420		
Busto Arsizio → Milan	50		

The average speed, cost, and emissions used in the numerical instances are shown in Table 10. Costs and emissions are reported in Euro and CO₂ equivalents per TEU, respectively. The parameters are consistent

with those used in Yee et al. (2021), Ambra et al. (2019a), Li et al. (2015), Barta et al. (2012), European Commission (2014), Marine Traffic (2020) and Demir et al. (2017).

Table 10: The speed, cost and emissions parameters used in the numerical analysis.

Arc type	Speed (km/h)	Cost (€/TEU)	Emissions (kg CO ₂ -eq/TEU)
Road	60	1.00/km	0.84/km
Railway	30	0.65/km	0.21/km
Waterway	10	0.25/km	0.356/km
Transshipment	2 hours	25	2.74