Intermodal Transport Optimization with Efficient Energy Usage and Reduced Greenhouse Gas Emission

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Abstract

With the growing concerns about global warming, there is mounting pressure on major logistics stakeholders to reduce greenhouse gas emissions and energy consumption in logistics operations. Intermodal Transportation emerges as a strategic solution for achieving both environmental and organizational objectives. Consequently, there is a need for optimized models to address this complex challenge. This paper presents a mixed integer linear program optimization model that concurrently optimizes parameters such as cost, transportation time, energy consumption, and greenhouse gas emissions, with a primary focus on energy consumption and greenhouse gas emission reduction. To ensure consistency, the mixed-integer linear program uses coefficients for certain variables. Given the diverse advantages and disadvantages of different transportation modes, achieving the right balance is crucial. Integrating mode selection with route choice plays a significant role in optimizing intermodal transport operations. The development of an optimized intermodal transport model considering the stated objectives proves to be an effective approach in aligning with environmental and organizational goals. The proposed model evaluates individual objectives during transportation and at transshipment locations. This enables stakeholders to gain detailed insights into where efforts should be concentrated to achieve desired outcomes. The model is applied to a sample case study, producing a set of solution pathways for mode choice and route selection that optimize greenhouse gas emissions, energy consumption, and overall operational costs.
Keywords: Intermodal transportation; multi-mode transportation; decarbonization; consolidation; full container load

@@1. Introduction

The role that freight transport plays in the global economy cannot be overlooked, given its significant impact on national GDP. According to Statista (2023), freight transport accounts for approximately 15%of the national GDP in China and about 6% in the United States (US), as reported by the US Bureau of Transportation Statistics (2022). Annually, the US alone sees the movement of billions of tons of goods across the nation through various transportation modes, including sea (e.g., ships), railway (e.g., trains), and road (e.g., trucks), refereed to as intermodal transportation. While freight transport contributes to the national economy Wang et al. (2021), the resulting greenhouse gas (GHG) emissions from freight movement are a serious concern.

With a steady increase in population, the surge in freight movement has consequently led to increased carbonization, positioning it as one of the most environmentally and socially harmful economic activities Fulzele and Shankar (2023). Scientific studies have emphasized the significant impact of transportation logistics on both energy consumption and carbon emissions, making it a major contributor to global warming Kaewfak et al. (2021). Despite the tremendous efforts made over the years to increase the effectiveness and efficiency of freight movement, it has persistently remained detrimental to the environment Bektaş et al. (2019). Compounding this issue is the heavy reliance on petroleum products as the primary energy source for freight movement. Consequently, countries all around the world have put incentives, laws, and regulations in place to help create a healthier environment for improved weather conditions and national progress Linton et al. (2020).

To combat the increasing carbonization from freight transport, major stakeholders are actively pursuing optimized operational strategies or technologies to reduce energy consumption and cut GHG

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emissions. Regional or national mandatory emission reduction programs, such as Cap-and-Trade (C&T) He et al. (2012), are being established to foster the development of a sustainable economy and environment. Also, international climate change agreements now prioritize decarbonization efforts due to the established connection between GHG emissions and increasing global warming Bektaş et al. (2019). This shift affects freight transport, distribution, planning, and control, necessitating changes in traditional approaches over distribution networks. Hence, it is especially important for businesses to consider decarbonization efforts when making logistics decisions Choudhary et al. (2021).

In light of this, there is a pressing need to explore alternatives that encourage decarbonization, with intermodal transportation emerging as a critical solution avenue. Intermodal transport involves movement of goods from one origin to a final destination using at least two modes of transport with transfer from one mode to another at transshipment points. It can be categorized into three phases as discussed below Archetti et al. (2022).

Pre-haul phase involves transporting goods from the origin, usually a warehouse, to a transshipment terminal where there is a change in mode. Typically, pre-haul is conducted using road transportation. Second, long-haul phase mostly covers the longer distance and can be accomplished through rail, waterways, or air transportation. Long-haul transport via these modes is often more cost-effective than other modes for extended distances and is frequently necessary. Lastly, end-haul phase, known as the last mile, represents the final stage of transportation to the final lo cation. Similar to pre-haul, end-haul is predominantly done by road transportation.

According to Pizzol (2019), intermodal transport is becoming a promising approach for carbon reduction in freight logistics due to the utilization of different transport m odes. To substantiate the effectiveness of advocating intermodal freight transportation for decarbonization without compromising operational goals, it is essential to consider the following rationale. Intermodal transport, commonly integrating sea and rail modes, has shown to generate lower carbon emissions when compared to only conventional road transport Bouchery and Fransoo (2015). This is because trains and barges used in rail and water intermodal transport contributes a smaller amount of carbon emissions than trucks. Also, container ships, particularly used long-distance transport, have been identified to have low energy usage per ton-mile during freight transport highlighting it as contributors to decarbonization efforts. Consequently, the key advantage will be in the ability of intermodal freight transport to compete with single modes on cost. By achieving cost equality or reduction, the economic benefits of freight logistics can be maintained while simultaneously enhancing decarbonization, thus making intermodal transport an attractive and sustainable solution.

Despite its numerous advantages, intermodal transport faces certain notable challenges. According to Bouchery and Fransoo (2015) one of such challenge is the extended transport time it incurs, which is primarily due to the additional intermediate nodes, which is not the case in singular modes. Also, in many instances, utilizing intermodal transport tends to increase travel distances Archetti et al. (2022), hereby contributing to higher carbon emissions, unless the covered distances are significantly reduced, resulting in emissions smaller than those of just one mode. Additionally, customers may have specific transport requirements, such as adherence to specific time windows and making use of intermodal transport may not be able to meet these requirements. Lastly,

The remaining sections of this paper are organized as follows. Section 2 presents a literature review on the previous research on intermodal transport optimization and decarbonizaiton. Section 3 introduces the problem description in depth. In Section 4, we discuss our optimization model proposed. In Section 5, we discuss our computational experiments together with the insights obtained from the sensitivity analysis. Section 6 concludes the paper and gives direction on future research.

@@ Literature review

In this section, we explore the existing body of research focused on freight intermodal transport, examining the challenges in previous literature providing a pathway for the problem and solution proposed in this paper. Despite the wealth of studies in this domain, they have notably fallen short in addressing the full extent of sustainable model development in intermodal transport. While these efforts have significantly contributed to decision-making processes amongst other things, there exists some noticeable gaps in the of sustainability efforts within the framework of intermodal transport optimization.

2.1 Freight intermodal transport optimization

Freight intermodal transport optimization problems has garnered significant attention, attracting interest from earlier research Choong et al. (2002) as well as more recent literature Ning et al. (2023); Chen et al. (2023). Choong et al. (2002) developed a model to tackle the complexities of intermodal freight transportation, they innovated an integer programming approach to reduce the costs associated with the movement of containers. Their results emphasized the significance of planning in selecting transportation modes and managing containers. Dynamic programming was employed by Hao and Yue (2016) to optimize transportation route, concentrating on balancing stakeholders objectives while focusing on minimizing both time and cost. Through experimentation, they were able to find the best intermodal route combination and an optimized total transportation cost and time.Frazila and Zukhruf (2017) addressed the optimization of a intermodal freight transportation network, considering uncertainties in demand and traffic flow with an objective to minimize total transportation costs involving transshipment locations and modal choices. To solve this problem, they proposed a discrete stochastic optimization model and used Monte Carlo simulations and a genetic local search algorithm to effectively manage uncertainties and identify optimal transportation and transshipment decisions. Wang and Meng (2017) advanced this field by proposing a mixed-integer nonlinear and non-convex programming model to tackle a discrete network design problem for freight intermodal transport. Their results showed that network design and planning could be very beneficial if properly optimized.

Subsequent research works like Guan (2020) developed a model for intermodal route selection, integrating variables like transportation cost, safety, and route selection with the primary goal of minimizing transportation expenses. The problem considered by Wagenaar et al. (2021) involved the complex task of planning intermodal freight networks operations involving long-term commitments and operational disruptions. They introduce a novel approach that combines reduced-sized models for specific cases combined with scenario-based and trip-based heuristics in a hybrid search loop. Results obtained in their study demonstrated substantial improvements in planning efficiency for real-sized cases. Luo et al. (2021) took it a little further by formulating a reconstruction model focuses on route planning that may require the reconstruction of lines or nodes to facilitate transport by determining optimal routes, modes of transport, and necessary reconstructions. To address the optimization of a sea-rail intermodal transportation corridor Chen et al. (2023) focused on maximizing transportation profits. They introduced a novel approach that integrates known and stated preference data to construct utility functions and route choice models coupled with a programming model. Their results provide specific operational recommendations that significantly enhances the profitability and attractiveness of the intermodal route selection, particularly for the transportation of high-value shipments.

To validate their effectiveness, several studies applied the developed optimization methods to real cases. Wang et al. (2018) used a mixed-integer linear programming model to solve an intermodal network design problem and developed a memetic algorithm. Their approach was applied to optimize a Turkish network dataset. Mostert et al. (2018) applied the bi-objective mathematical model to a case study in Belgium in optimizing intermodal networks flow. In another application, Göçmen and Erol (2019) employed mathematical modelling and heuristic algorithms for international intermodal transport problems. A three-mode intermodal freight transport optimization model with operational and environmental objectives was developed by Dai et al. (2018) and applied to a real-life hinterland logistics network in Yangtze River Economic Belt. Their results demonstrated a significant change in the traffic flow across intermodal routes, successfully attaining the objectives of emissions reduction. Finally, Chen et al. (2023) focused on selecting international trade transportation mode. They formulate a programming model with objective to optimize transportation profits in an intermodal network. This was applied to a Japan-Europe case study that utilizes, sea-rail transport and considers sailing speed and size of ship.

While these studies have greatly contributed intermodal transport optimization, we take this further by developing a model that incorporates associated energy sources along the transportation network. This adds an extra layer to the problem because realistically, during intermodal route planning, potential energy sources for the different modes have to be considered and to the best of our knowledge, no study has incorporated potential energy sources into intermodal transport optimization. We also consider the capacity of the potential energy sources along the transportation routes adding to the novelty of our work.

@@ Decarbonization in intermodal freight transport

The existing body of research on intermodal transport initially concentrated on models and algorithms tailored to operational challenges. These studies, while methodically robust, often overlooked intermodal transport optimization involving decarbonization efforts. This gap was consistent until a paradigm shift towards environmental sustainability began to influence the field. The next phase saw the integration of environmental factors into optimization models. A mixed integer linear programming model was introduced by Kabadurmus and Erdogan (2020) to study the complex task of designing sustainable and reliable intermodal supply chains. They considered economic, decarbonization, and risk factors incorporating a carbon cap-and-trade scheme and a risk threshold. Whereas in their own study, Zhang et al. (2021b) addressed the optimization of transportation time and cost including carbon emission cost. This involves low-carbon intermodal transportation routes under dual uncertainties through a hybrid robust stochastic optimization model. Their experimental results demonstrate the impacts of optimizing intermodal transportation route selection, mode choice, and overall costs and provided decision-makers with a valuable tool for designing more sustainable and efficient transportation networks.

This trend of environmental consciousness in intermodal transportation was further underscored by Heinold et al. (2023). They tackled the problem that employed eco-labels in estimating transportation emissions and associated cost when dynamically routing orders in an intermodal network. They proposed a multiobjective sequential decision process and a reinforcement learning method: value function approximation. Xianshuo (2021) studied optimizing green intermodal transportation routes by minimizing comprehensive costs and carbon emissions. They emphasize the importance of environmentally friendly and cost-effective transportation solutions by proposing a model that quantifies carbon emissions as part of the total cost. Experimental results showed solutions that effectively reduces both carbon emissions and transportation costs, demonstrating the feasibility of achieving sustainable and cost-effective transportation paths. Yang et al. (2023) considered the optimization of highway-railway intermodal transport routes through an optimization model that simultaneously minimizes transportation cost, time, and carbon emissions in order to enhance efficiency and decarbonization efforts. Their results provides practical intermodal transport strategies that prmotes decarbonization and reduces costs.

A critical component of decarbonization efforts is the incorporation of carbon tax policies into intermodal transport routing strategies with an aim to optimize routes for efficiency and cost-effectiveness and also to actively mitigate GHG emissions. In light of this, Sun and Lang (2015) applied the carbon tax policy in developing a sustainable intermodal transport network, which includes routing of both fixed and flexible freight transportation services. This approach represents an innovative attempt to balance decarbonization efforts with operational flexibility in intermodal transportation. Duan and Heragu (2015) also integrated the carbon tax policy in their study of the U.S. intermodal coal transportation problem. Their research was particularly notable for identifying a breakeven point for the carbon tax rate. Their model aimed to minimize GHG emissions while avoiding excessive increases in intermodal transportation costs, highlighting the delicate balance between environmental sustainability and economic feasibility. Zhang et al. (2021a) utilized it in addressing China's railway-dominated intermodal route selection problem, demonstrating the policy's applicability in different geographical contexts and transportation modes.

To further enhance the research domain, Zhang et al. (2017) explored a low-carbon intermodal routing problem that incorporated the carbon tax policy along with hard delivery time windows. Their findings suggested that relaxing strict time window constraints could enhance the effectiveness of the carbon tax policy in decarbonization. These studies indicates the increasing relevance of decarbonization policies in diverse aspects of intermodal transportation. Sherafati et al. (2020) also introduces a novel supply chain network design problem focused on achieving sustainability by integrating economic, environmental, and social dimensions, with a specific emphasis on incorporating carbon p olicies. A mixed uncertainty approach is proposed to address uncertain emission parameters with models that consider carbon cap, carbon tax, carbon cap-and-trade, and carbon offset policies.

To buttress the efforts of decarbonization in intermodal transportation, while also incorporating some elements from previous research works like the carbon tax policy, we develop a model that considers the multiple carbon tax policies across different geographical l ocations. Previous studies mostly consider the same carbon tax policy across the intermodal transportation network, which does not provide an accurate representation of the problem. Also, we specifically concentrate on the different carbon emission limit for different cities across the intermodal network, providing a realistic and feasible approach to optimizing decarbonization efforts together with the intermodal network.

@@ Container consolidation in freight transport

Since the introduction of freight consolidation in the 1950's, there has been notable research efforts in maximizing it's potential. It involves placing shipments in large containers, minimizing transshipment time, and reducing transportation and storage costs. In the process of consolidating freight, smaller volumes of shipments are combined into larger bundles at a consolidation center and are subsequently transported collectively through transportation services. Qin et al. (2014) initially presented the freight consolidation and containerization problem focusing on the shipment of textile products. Building on the work of Qin et al. (2014), Melo and Ribeiro (2015) redefined the freight consolidation and containerization model. Their approach involved combining items and applying mixed-integer programming to optimize the problem with results showing that their approach outperforms results from the previous literature. Also, Fan et al. (2019) presented an analytical model for the systematic analysis of flow consolidation involving both container and cargo consolidation taking into consideration shipment distance and cargo type. They concluded from obtained results that there is a significant cost and emission reduction through the optimization of freight consolidation.

Also, Tiwari et al. (2021) proposed a freight consolidation and containerization multi-objective optimization model that considers both carbon tax policies and environmental concerns by comparing scenarios with and without carbon tax policies. Based on their results, adopting a shipment containerization strategy involving carbon tax regulations yields favorable results in transportation costs and carbon emissions when compared with policies without carbon tax. In the case of Hanbazazah et al. (2019) they studied the time constrained freight consolidation problem with divisible shipment. They proposed a mixed-integer programming model the considers piecewise costs, and delivery time windows and an algorithm was employed to solve to a real-life case study. Huang et al. (2020) addressed the problem involved with making routing and consolidation decisions. An MIP model with the objective of minimizing the total cost was formulated and solved by Lagrangian Relaxation based algorithm Trapp et al. (2020) developed and integer optimization model to solve the problem faced by shipping intermediaries. Their model considers multiple travels, shipments, retailers and container types with an aim to minimize emission and transportation cost. Results showed that competition during freight transport yields economic gains but has bad environmental implications.

Van Heeswijk et al. (2019) studies the problem of dispatching faced by a consolidation center with stochastic arrivals. They modelled the problem as a variant of delivery dispatch problem with delivery time windows and formulated an appropriate Markov decision model. They developed an approximate dynamic programming algorithm and an integer linear program to solve the problem with result outperforming benchmark standards with even better performance during flexible dispatch windows. Camur et al. (2022) studied the problem of optimizing transportation modes and shipment consolidation to enhance cost-efficiency and su stainability. To achieve this, they introduced a dynamic multi-period multi-commodity network flow model and a novel heuristic approach that utilized a rolling time horizon. Their model considers transportation costs and deadlines, and providing a framework to strategically optimize logistics operations. Through a detailed case study of GE Gas Power's logistics operations, they demonstrate the potential of the proposed solution to effectively balance cost, time, and consolidation requirements in real-world logistics scenarios.

Recognizing the efforts of Camur et al. (2022) been the closest to our work, we focus on a variant of the problem by incorporation carbon emission constraints to the consolidation problem. Adding carbon emission constraints changes the dynamics of the problem because it changes the potential route and/or mode selection for a set of containers in the case where it is feasible to utilized the capacity of certain routes and/or mode but the limit of the allowable carbon emission will not permit the container to flow along that route. Starting from the source nodes, a limit in carbon emmision may affect the delivery time of the shipments to the consolidation center posing a potential change to initial intermodal route or mode. Giving the stated contributions, we believe our work will further enhance the body of knowledge in intermodal transport optimization for a multi-period multi-commodity network taking into consideration operational efforts that promotes decarboonization.

@@ Problem Description

In this work, we focus on an inter modal transportation optimization problem that incorporates container consolidation and carbon emissions considerations. The primary decision makers in this scenario could include transportation companies or manufacturing companies working with third party logistics providers. We also include several stakeholders, such as federal and local governments, which can impose environmental constraints on transportation operations. Our main objective is to identify an optimal transportation plan for each shipment within a given time horizon that minimizes cost while considering environmental impacts.

We consider three modes of transportation: road, railway, and sea. While shipments are transported via trucks on the road network, they are moved in containers via ships and trains on sea and railway networks, respectively. They travel through multiple locations including suppliers, switch points, stations, and demand locations. Stations are the locations where shipments are either consolidated or deconsolidated. Switch points represent transitions from one location to another, such as from Interstate 90 to Interstate 95 in the US. From a graph theory perspective, we represent each location as nodes, and the transportation modes that connect these locations are represented as edges.

Each location in the transportation network has associated energy infrastructures (e.g., EV stations, gas stations), which have a limited capacity for the company's use. Under these circumstances. the company aims to transport shipments from supply locations (e.g., warehouses, manufacturing facilities) to stations (i.e., train stations, ports) using the road network. After consolidating multiple shipments into containers, they are moved via railway and sea networks to different stations for decondolidation. Note that a container can switch between the railway and sea network if necessary. Also, as long as there is enough capacity, new shipments can be consolidated or existing ones can be deconsolidated from a container en route. From there, shipments are transported to demand locations, including distribution centers and customers, using the road network again.

We consider different container types with respect to their sizes. Further, we only consider full container load in our problem, as it plays the highest importance in reducing both logistics and environmental costs. The containers which are utilized has an associated fixed cost or operational cost depending on the problem owner. If the company owns its own containers, then operational costs are considered. Otherwise, the company pay a fixed cost to use an external container. We do not focus on truck consolidation, where the costs of shipments transported via the road network are evaluated based solely on transportation costs. We assume that the company packs multiple orders going to the same demand location within the same shipment.

Total carbon emissions depend on factors like the transportation mode and the energy resource utilized (Wang et al., 2023). Thus, we consider different vehicle types in each transportation mode. For instance, the company may consider utilizing electrical trucks and gasoline-based trucks, that vary in capacity, energy efficiency, and transportation costs. There are several studies considering carbon-emission tax schemes from a cost perspective (see Wang et al. (2015)). We adapt a similar approach For example, if the carbon tax rate is \$50 per tonne of CO_2 equivalent, and a company emits 10,000 tonnes of CO_2 equivalent in a year, the carbon tax would be calculated as $10,000 \times 50 =$ \$500,000.

Every shipment is associated with a specified pickup and delivery time windows. While pick up time enforces the time that the shipment can leave the supplier, the delivery time imposes when the shipment is needed at the demand location. If the shipment cannot be delivered on time, then a penalty is for late deliveries.

We finish this section by summarizing our assumptions.

- A feasible route exists for each shipment corresponding to a supply and demand pair.
- Partial shipments are not allowed; in other words, if a shipment occurs, the entire order is fulfilled.
- We assume that shipments can be feasibly placed in a container as long as the container's capacity is not exceeded.
- There is no capacity constraint for transporting shipments via the road network; however, the number of containers that can be utilized is restricted.
- Supply and demand locations of each shipment, transportation times, costs, availability of routes, and carbon emission coefficients are known a priori.
- Route availability does not change throughout the entire planning horizon. Considering disruptions and network resiliency will be included in our future research efforts (see ..).
- Containers are assumed to be at the required station in advance and we do not consider empty container routing. In other words, once a container finishes its route, we assume that one container becomes available for usage again in the system.
- Each container requires solely one energy resource and has the same average speed if they are transported on the same mode of transportation.

@@ Optimization Model

In this section, we provide a mixed-integer linear programming (MILP) model designed for the problem presented in Section 3. We first present sets, parameters, and variables in Tables 1, 2, and 3, respectively. We then illustrate our model and explain each constraint in detail.

Sets	**Definition**
V	nodes (i.e., locations such as stations, warehouses)
S	source nodes where $S \subset V$
I	intermediate nodes where $I \subset V$
D	demand nodes where $D \subset V$
E	edges (links between locations)
G	network where $G = (V, E)$
P	shipments
C	containers
R	energy resources
M^E	transportation modes with corresponding edges
M^F	FCL transportation with corresponding edges where $M^F \subset M^E$
T	time period (in weeks)

Table 1: Set definitions

IP:

Parameter	Definition
τ_{ijm}	transportation time taken to go from node i to node j with mode m
d_{ip}	whether node i is the demand node (destination) for shipment p
s_{ip}	whether node i is the supply node (origin) for shipment p
a_p	availability of shipment p to leave the supply location
υ_p	deadline of shipment p
α_p	penalty cost for violating deadline of shipment p
o_{ijmct}	operational cost of container c going from node i to node j with mode m at time t
λ_{ij}	number of FCL containers available at each time period on edge ij
e_{ijmc}	carbon emission coefficient in tons for transportation from node i to j with mode m in container c
κ_t	carbon tax rate enforced by government in a given year at time t
ξ_{ijmpt}	transportation cost of shipment p from node i to node j with mode m at time t
w_p	weight of shipment p
σ_{mc}	capacity of container c with mode m
ψ_{rit}	capacity of energy resource r in location i at time t
μ_{cr}	energy consumption rate of container c for energy resource r
Θ_{cr}	whether container c requires energy resource r

Table 2: Parameter definitions

Variables	
x_{ijmpt}	whether shipment p is transported from node i to node j with mode m at time period t
y_{ijmct}	whether container c travels from node i to node j with mode m at time period t
z_{pc}	whether shipment p is placed in container c
ν_p	arrival time of shipment p
l_p	lateness of shipment p

Table 3: Variable definitions

$$\min \sum_{(i,j)\in E}\sum_{m\in M^E}\sum_{p\in P}\sum_{t\in T}\xi_{ijmpt}x_{ijmpt} + \sum_{(i,j)\in E}\sum_{m\in M^F}\sum_{c\in C}\sum_{t\in T} e_{ijmc}\kappa_t y_{ijmct}+ \tag{1a}$$

$$\sum_{(i,j)\in E}\sum_{m\in M^F}\sum_{c\in C}\sum_{t\in T} y_{ijmct}o_{ijmct} + \sum_{p\in P}\alpha_p l_p$$

$$\sum_{j\in N(i)}\sum_{m\in M^E}\sum_{t\in T} x_{ijmpt} = s_{ip}, \forall i \in S, p \in P \tag{1b}$$

$$\sum_{(i,j)\in E: i\in S}\sum_{m\in M^E}\sum_{t\in T: t\leq a_p} x_{ijmpt} = 0, p \in P \tag{1c}$$

$$\sum_{j\in N(i)}\sum_{m\in M^E} x_{ijmpt} - \sum_{j:i\in N(j)}\sum_{m\in M^E} x_{jimp(t-\tau_{jim})} = 0, \forall i \in I, p \in P, t \in T \tag{1d}$$

$$\sum_{i:(i,j)\in E}\sum_{m\in M^E}\sum_{t\in T} x_{ijmpt} = d_{jp}, \forall j \in D, p \in P \tag{1e}$$

$$x_{ijmpt} \leq \sum_{c\in C} z_{pc}y_{ijmct}, \forall (i,j) \in E, m \in M^F, p \in P \tag{1f}$$

$$\sum_{c\in C} z_{pc} \leq 1, p \in P \tag{1g}$$

$$\sum_{j\in N(i)} y_{ijmct} \leq 1, i \in I, m \in M^F, c \in C, t \in T \tag{1h}$$

$$\sum_{(i',j')\in E}\sum_{m'\in M^F} y_{i'j'm'c(t+\tau_{ijm}-1)} \leq |T|(1 - y_{ijmct}), (i,j) \in E, m \in M^F, c \in C, t \in T \tag{1i}$$

$$\sum_{c\in C} y_{ijmct} \leq \lambda_{ij}, (i,j) \in E, m \in M^F, t \in T \tag{1j}$$

$$\sum_{p\in P} w_p z_{pc} x_{ijmpt} \leq \sigma_{mc}, (i,j) \in E, m \in M^F, c \in C, t \in T \tag{1k}$$

$$\sum_{j\in N(i)} \sum_{m\in M^F} \sum_{c\in C} \Theta_{cr} \mu_{cr} y_{ijmct} \leq \psi_{rit}, r \in R, i \in I, t \in T \tag{1l}$$

$$(t + \tau_{ijm}) x_{ijmpt} \leq \nu_p, \forall (i,j) \in E : j \in D, p \in P, m \in M^E, t \in T : d_{jp} = 1 \tag{1m}$$

$$(t + \tau_{ijm}) + |T|(1 - x_{ijmpt}) \geq \nu_p, \forall (i,j) \in E : j \in D, m \in M^E, p \in P, t \in T : d_{jp} = 1 \tag{1n}$$

$$\nu_p \leq \upsilon_p + l_p, p \in P \tag{1o}$$

$$x_{ijmpt} \in \{0,1\}, y_{ijmct} \in \{0,1\}, z_{pc} \in \{0,1\}, \nu_p \in \mathbb{Z}_+, l_p \in \mathbb{Z}_+ \tag{1p}$$

The objective function (1a) aims to minimize the total logistics cost, which consists of four components: a) total transportation cost by traversing an edge, b) the total carbon tax required by the local or federal governments, c) total fixed / operational cost paid for each container used on railway and sea networks, and d) penalty cost for delaying a shipment.

Based on the network flow, Constraint (1b)-(1e) guarantee that every shipment can be transported from a supply node to its destination through all time periods, in which there is no available supply before a time threshold (1c). Since the shipment needs different time periods to transport between nodes, Constraint (1d) considers the flow balance of each intermediate node in each time period.

For shipments in FCL transportation, Constraint (1f) assigns a container for them on each edge. Besides, each shipment can only be stored in one container, which is shown in Constraint (1g). Constraint (1h) makes sure the movement of each container follows shipments inside it. Also, the container will not be available when it is on the way to the destination. After reaching the destination, the container can be used again in any intermediate node, which is ensured by Constraint (1i). Additionally, Constraint (1h) assumes the company can book at most a certain number of containers on each intermediate edge at every time period. Since the container has limited capacity, Constraint (1k) guarantees that the total weight of shipments in a container will not exceed its capacity. For the requirement of carbon emission, Constraint (1l) calculates total carbon emission based on each intermediate node, and makes sure that cannot be more than the given threshold during each time period.

Finally, Constraint (1m) and (1n) compute the arrival time of each shipment, which is a positive integer variable. Combining with Constraint (1o), the late arrival shipment will bring an additional penalty cost to the objective function.