Traffic & Transportation

Multi-Objective Optimisation of Container with Food Cold Chain Using Multimodal Transport under Uncertainties in Network Structure and Ad-Hoc Situations

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ABSTRACT
With the increasing security of food supply chains, ensuring the optimal transportation of perishable goods has become crucial. Various options and modes of transportation offer significant advantages in terms of efficiency, cost-effectiveness and environmental sustainability. However, the uncertainty associated with network structure and unforeseen events would pose unique challenges for optimising the food cold chain container routing. This research aims to develop a multi-objective optimisation model for the container-based food cold chain transportation system. Considering the random failure of the network nodes scenario, a container with a cold chain multimodal routing optimisation model was constructed. The optimisation goal is to minimise transportation costs, carbon emission costs and total transportation time. The research adopted a mixed-integer optimisation model by linearisation technology. Gurobi was used to solve the problem. The model and solution were then verified by the empirical data. The findings uncover the new influence of the node failure on the multimodal route design, as well as different parameters on the cost of multimodal routes for better decision-making. The research contributes to the development of more resilient and efficient food cold chain transportation systems through the new conditions of five constraints in the proposed model, which is capable of adapting to uncertainties in network structure and ad-hoc situations.

KEYWORDS
multimodal transportation; cold chain; container; network structure uncertainties; multi-objective optimisation.

1. INTRODUCTION

The transportation of perishable goods, specifically fruits and vegetables, requires meticulous planning and execution to ensure the preservation of their quality and freshness [1]. In today's complex transportation networks, there is a growing need to optimise the container with a food cold chain using multimodal transport. This approach has garnered significant attention for its potential to enhance the transportation process, especially for addressing the challenges related to network structure uncertainty and ad-hoc situations. For example, the ad-hoc situations due to climatic conditions, such as the failure of a transportation hub node (extreme weather such as floods, earthquakes and snowstorms in the hub node city), the transportation line would be congested or become invalid [2]. Multimodal transport then should be considered as the transport process can be completed by two or more modes of transport of modal, which also contains two or more connections and transfers. It involves a mixture of modes such as road, rail, air and sea. Unlike traditional single-mode transport, multimodal transport offers greater flexibility, efficiency, low carbon emissions [3-6] and resilience [7-12] in ensuring on-time delivery [13] and maintaining food cold chain integrity [14].

Multimodal transportation is considered a transportation method with less environmental impact [6,15], which attracts researchers' interest. Carbon pricing has a significant effect on multimodal transportation. The increases in carbon prices could promote roadway transport transfer to waterway transport and railway transport, which would decrease the total carbon emissions and make the structure of the multimodal transport network become more sparse [5]. Somsai et al. [6] found that using a dry port with rail connections could reduce transportation and carbon costs by 54.3%. Therefore, this paper will consider carbon emission costs in the multimodal transport optimising model.

In the context of scheduling optimisation for container cold chain multimodal transportation, it is imperative to incorporate additional considerations such as refrigeration expenses and the operational costs associated with specialised equipment. Consequently, the transportation process within this domain encompasses a variety of cost components, including refrigeration costs [14], transportation fees and transfer expenses [15-16]. When optimising the routing of containerised cold chain multimodal transport, the objective function extends beyond mere total cost minimisation to include transportation duration and carbon emissions. As such, it is feasible to construct a multimodal transportation scheduling optimisation model tailored for fresh food, which holistically accounts for cost efficiency, transportation time and environmental impact in terms of carbon emissions [14,17].

Containerised cold chain multimodal transportation involves multiple stakeholders, various modes of transport and diverse transportation equipment, alongside the necessity for continuous refrigeration of cold chain containers throughout the journey. This complex transportation process is characterised by numerous uncertain factors. Extensive research has been conducted on planning theories under uncertainty, with these theories being applied and validated through case studies. To address the impact of uncertain factors on the organisation of multimodal transportation, it is essential to develop an optimisation model that explicitly incorporates these uncertainties. Key considerations include demand uncertainty [18], the variability of railway transport capacity and the optimisation of multimodal transportation routes under road transport congestion scenarios [16]. In terms of model-solving approaches, enhanced dynamic programming algorithms [19], solver-based methods [14, 19] and heuristic algorithms [20, 37] have demonstrated robust performance. Consequently, this paper will account for uncertainties in network structure and construct a containerised cold chain multimodal routing optimisation model. The model aims to minimise transportation costs, carbon emission costs and total transportation time as its optimisation objectives. Gurobi will be used to solve the problem.

Complex network theory has been widely applied across various fields, such as communication networks, social networks, power grids and transportation networks. It has proven effective in analysing network structures and characteristics [21-26]. Researchers in the transportation field have utilised this theory to evaluate and construct transportation networks, analyse the structural characteristics of urban road networks and identify critical nodes [24-26]. Shiguang, Wang et al. [24] employed a dual modelling approach based on complex network theory to analyse the structure of urban road networks. They compared the topological structures of road networks in six cities to identify significant similarities among clusters. Additionally, by simulating local attacks on weighted road networks and integrating network efficiency with node importance, they identified critical nodes [25]. However, research on the structural uncertainties of multimodal transportation networks remains limited. Therefore, this paper will consider the scenario of uncertainties in network structure when constructing a containerised cold chain multimodal routing optimisation model.

Container cold chain transportation faces challenges in various aspects, including industrial and transportation environments, infrastructure and refrigeration technology. The refrigeration equipment within refrigerated containers can maintain the internal temperature, thereby ensuring the integrity of the cold chain during transportation. As a crucial transport unit in the cold chain multimodal transportation system, containers have the potential to enhance the efficiency and reliability of cold chain logistics. However, refrigerated containers are highly dependent on their temperature control capabilities. Container carriers must assess risks associated with inadequate pre-cooling of goods, excessive loading times, improper stacking of cargo and power system failures, and implement appropriate measures to improve the safety performance of the cold chain process [27]. Diesel, as a source of operational energy for containers, is unsustainable. Therefore, it is necessary to conduct research on the cooling materials and components used in railway-road integrated container cold chain transportation. By utilising electricity as the energy source, energy consumption, operating costs and emissions were reduced by 86.7%, 91.6% and 78.5%, respectively [28]. Consequently, container cold chain transportation demonstrates significant advantages and promising prospects in terms of energy consumption, operating costs and carbon emissions [29].

Although several studies have addressed container transportation in the food chain, there is a dearth of literature that specifically focuses on optimising the transportation of perishable goods like fruits and vegetables using multimodal transport in relation to the challenges related to network structure uncertainty and ad-hoc situations. Many of them have overlooked the impact of ad-hoc situations, especially those arising from unforeseen events such as natural disasters, emergencies or pandemics. For example, Guo et al. [8] only considered the location selection strategy of emergency rescue facilities in the multimodal transport network. Moreover, the subside policy [30-31], cooperative [32], route selection [2] are considered in multimodal transportation. Rossi et al. [11] primarily investigated multimodal transportation using trains for the optimisation perishable food supply chain but without considering ad-hoc situations and other modes of transportation. Multimodal transport faces an uncertain environment during transportation [14], including time uncertainty [33-35], demand uncertainty [36-38]. Azani et al. [39] developed an optimisation model for food supply chains in the context of Covid-19 but overlooked the network structure uncertainties. Sharifi et al. [11] proposed a multi-objective robust fuzzy stochastic programming model for sustainable, resilient and responsive agri-food supply chains to optimise performance amidst uncertainties like population growth and pandemics. There is a need for a comprehensive optimisation model that systematically integrates the considerations of fruit and vegetable transportation, network structure uncertainties and ad-hoc situations.

To address this research gap, the research aims to develop a multi-objective optimisation model for the container-based food cold chain transportation system, seeking robust and resilient solutions for decision-makers in the logistics industry. The research adopted mathematical modelling and optimisation algorithms techniques to address the optimisation problem. First, a container cold chain multimodal routing optimisation model was constructed by considering the random failure of the network nodes scenario. The hierarchical sequence method was used to clarify the multi-objective. Gurobi was then adopted to solve the mathematical problem. Lastly, local empirical data were used to analyse and verify the proposed model, together with the sensitivity analysis. The research would provide insights into designing strategies that can adapt to uncertainties in network structure and handle ad-hoc situations, ultimately improving the transportation of perishable goods, even in challenging circumstances.

2. MODELLING METHODOLOGY

In the realm of transportation, a multimodal transport network is a complex structure comprised of interconnected nodes and edges. Each pair of nodes within this network exhibits the potential to be serviced by one, two or even three distinct transport modes. These modes commonly encompass the roadway transport network, railway transport network, waterway transport network and airline transport network. The integration of multiple transport modes within a single network would help to increase reliability and flexibility in response to unforeseen events or disruptions.

2.1 Problem description

Container cold chain multimodal transport involves multiple transportation routes, hubs and operating entities. This research considers the optimisation modelling of multimodal transportation paths under the condition of uncertain network structure caused by the random failure of nodes. The multimodal carrier designs the optimal transportation plan on the basis of the existing transportation network and transportation information. Therefore, the modelling analysis is carried out from the perspective of the multimodal transport carrier. Considering the random failure of nodes in the multimodal transport network, the establishment of a container cold chain multimodal transport route optimisation model becomes imperative. Subsequently, a comparative analysis of network structure and transport routes prior to and following node failure ensues. It is elucidated through *Figure 1* that the multimodal transport network, integrating road, rail and water transportation modes, encompasses a total of 13 nodes. In the event of the 13th node's failure, the consequent breakdown would permeate into multiple road segments originating from its interconnectedness. Specifically, if the transportation path from node 1 to node 9 encompasses node 13, the failure of the latter would precipitate a modification in the multimodal transportation route. Thus, it is crucial to acknowledge that the node failure occasion heralds alterations in the transportation route.

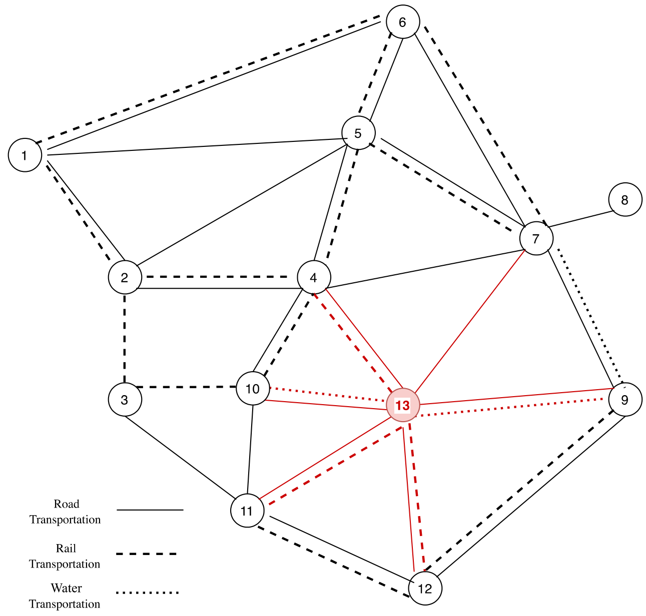

Figure 1 – The multimodal transport network with node 13 failed

2.2 Mathematical model for the multimodal routing problem with node failure

Assumptions and notations

To establish a mathematical model for the multimodal routing problem with node failure, it is necessary to make certain assumptions to simplify the problem and facilitate the modelling process.

Here are some possible assumptions that can be made:

1) The container will not be unpacked and consolidated during the transportation and trans- shipment process.
2) There is only one transportation mode that will be adopted by carriers between nodes.
3) The shelf life of cold-chain container transportation is calculated from the beginning of the transportation process.
4) Each node has facilities and equipment to ensure the cold chain transportation of containers.
5) The transport speed between two nodes is a constant value.
6) The storage cost at the transfer station is not considered. The goods will not be stored at the transfer station for a long time.
7) The transportation capacity cannot exceed the maximum load capacity of the container.

There is a multimodal transport network$G, G = (V, E, W, K)$, and its various parameters are described as follows:

V : Node set;
E : Transportation arc set;
W: Transportation arc weight set;
N : The total number of nodes in the network G;
K: The set of transportation modes from node i to node j;
d_{ij}: The distance from node i to node j, $i, j \in V$;
ω_{ij}:: In the topology of the network G, the shortest distance from node i to node j is defined as the number of edges on the shortest path connecting these two nodes, $i, j \in V$;
C_c: Production cost of goods c (CNY/kg);
C_k: Transportation cost by mode k (CNY/km);
C_o: Cooling cost (CNY/h);
φ_c: The acceptance rate of product c;
C_e: Cost per unit of carbon emissions (CNY/kg);
SL_c: The validity period of product c;
QRP_c: The point of quality decline of product c;
$t^r_{kk'}$: The time for a single transfer of unit weight cargo from the mode of transport k to k', where

$k \neq k'$;
$c^{r}_{kk'}$: The cost of a single transshipment unit weight cargo from the mode of transport k to k', where $k \neq k'$;
k: Transportation modes, including road (k= 1), railway (k= 2), waterway (k= 3);
D_{jc}: Destination j's demand for product c;
O_{ic}: The supply of product c at place i ;
v^{sk}_{ij}: Transportation speed from i to j via transportation mode k;
T_k : The transportation time from i to j via a certain mode of transportation k;
T_r : The total transit time from the start point to the end point;
T_t : The total transportation time from the start point to the end point;
T: The total time of the transportation plan, including the T_r and T_t ;
T^U : The maximum allowable delivery time from the place of supply to the destination;
T^D: The minimum allowable delivery time from the place of supply to the destination;
C_{sk}: The carbon emissions produced by the transport unit distance of the k transportation mode;
$C^{re}_{kk'}$: The carbon emission per unit weight of cargo in a single transfer from the mode of transport k to k', where $k \neq k'$.

Decision variables:

$$z^{r}_{ij} = \begin{cases} 1 & \text{If transfer occurs at point } j, \\ 0 & \text{otherwise}. \end{cases} \quad (1)$$

$$y^{k}_{ij} = \begin{cases} 1 & \text{From } i \text{ to } j \text{ by transport mode } k, \\ 0 & \text{otherwise}. \end{cases} \quad (2)$$

2.3 Model formulation

A multi-objective optimisation model of a container cold chain multimodal transportation path is created with the intention of minimising the overall cost and time while taking into account the uncertain transportation scenarios of the network structure brought on by the random failure of nodes.

Related cost analysis

The total cost contains transportation cost, transshipment cost, cargo loss cost, refrigeration cost and carbon emission cost. Transportation time and transit time are included in the overall transportation time. Each indicator is described as follows:

Z_1, Z_2, Z_3 and Z_4 are the transportation cost, transshipment cost, cargo loss cost, refrigeration cost and carbon emissions cost. The cargo loss cost refers to the loss during transportation. After the quality drops to a certain threshold, the seller will consider a loss of profit. This part of the loss is the risk of not obtaining profit after the goods are produced. Based on the linear relationship between the quality of fresh goods and time ratio, which is the transportation time to the shelf life of fresh goods. As shown in *Figure 2*, the specific value at which the quality of the goods begins to decline is the QRP (quality reduction point). Goods c are shipped to the destination by cold chain. There is an acceptance rate φ_c (as shown in the *Equation (5)*) for the product, so the cost of cargo loss is the loss cost caused by the acceptance rate [14], as in the *Equation (6)*.

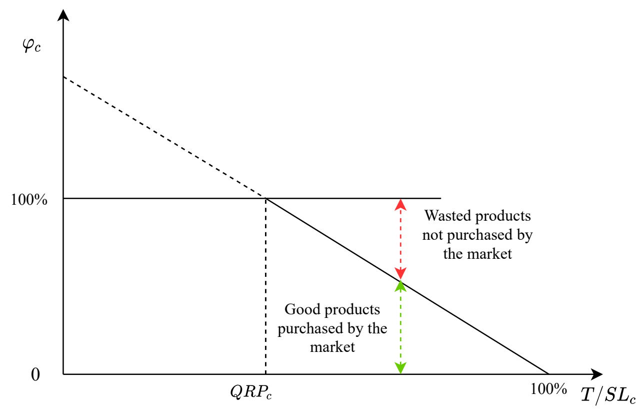

Figure 2 – Purchase probability function

$$Z_1 = \sum_{k\in K}\sum_{i,j\in V} d_{ij} \cdot y_{ij}^k \cdot C_k \cdot D_{jc} \tag{3}$$

$$Z_2 = \sum_{k,k'\in K}\sum_{i,j\in V} z_{ij}^r \cdot c_{kk'}^r \cdot D_{jc} \tag{4}$$

$$\varphi_c = min\{\frac{1 - T/SL_c}{1 - QRP_c}, 1\} \tag{5}$$

$$Z_3 = (1 - \varphi_c) \cdot D_{jc} \cdot C_c \tag{6}$$

$$T_t = \sum_{k\in K}\sum_{i,j\in V} y_{ij}^k \cdot d_{ij}/v_{ij}^{sk} \tag{7}$$

$$T_r = \sum_{k,k'\in K}\sum_{i,j\in V} t_{kk'}^r \cdot z_{ij}^r \cdot D_{jc} \tag{8}$$

$$Z_4 = \sum_{k,k'\in K}\sum_{i,j\in V}\left(y_{ij}^k \cdot d_{ij}/v_{ij}^{sk} + t_{kk'}^r \cdot z_{ij}^r\right) \cdot D_{jc} \cdot C_o \tag{9}$$

$$Z_{ce} = \sum_{k,k'\in K}\sum_{i,j\in V} (d_{ij} \cdot y_{ij}^k \cdot C_{sk} + z_{ij}^r \cdot C_{kk'}^{re}) \cdot D_{jc} \tag{10}$$

The transportation time of container cold chain multimodal transportation is shown in the *Equation (7)*, the transit time is shown in the *Equation (8)*, and the refrigeration cost is represented by Z_4. Carbon emissions are represented by Z_{ce}.

The total time of the transportation plan refers to the total time from the starting point to the destination of the goods, including the total transportation time T_t of each transportation mode and the total transit time T_r of the transit node.

$$T = \sum_{k\in K}\sum_{i,j\in V} y_{ij}^k \cdot d_{ij}/v_{ij}^{sk} + \sum_{k,k'\in K}\sum_{i,j\in V} t_{rj}^{kk'} \cdot z_{ij}^r \cdot D_{jc} \tag{11}$$

When designing the container cold chain multimodal transportation scheme, all costs and time need to be taken into consideration, so the total cost function Z_c, total time function Z_t (Z_t = T) and total carbon emissions are obtained. The function Z_{ce}, for the carrier, the lower the total cost, the shorter the total time, and the less carbon emissions, the better the transportation plan.

$$Z_c = Z_1 + Z_2 + Z_3 + Z_4 \tag{12}$$

$$Z_t = T_t + T_r \tag{13}$$

$$minZ_c = min\sum_{k,k'\in K}\sum_{i,j\in V} d_{ij} \cdot y_{ij}^k \cdot \left(C_k + \frac{C_0}{v_{ij}^{sk}}\right) \cdot D_{jc} + z_{ij}^r \cdot \left(c_{kk'}^r + t_{kk'}^r C_0\right) \cdot D_{jc} + (1 - \varphi_c) \cdot D_{jc} \cdot C_c \tag{14}$$

$$minZ_t = min\sum_{k,k'\in K}\sum_{i,j\in V} y_{ij}^k \cdot d_{ij}/v_{ij}^{sk} + t_{kk'}^r \cdot z_{ij}^r \cdot D_{jc} \tag{15}$$

$$minZ_{ce} = \sum_{k,k'\in K}\sum_{i,j\in V} (d_{ij} \cdot y_{ij}^k \cdot C_{sk} + z_{ij}^r \cdot C_{kk'}^{re}) \cdot D_{jc} \tag{16}$$

Considering that carbon emissions will be taxed in the future, we can multiply the carbon emissions by the carbon tax, as shown in the *Equation (17)*, so as to incorporate the objective function of carbon emissions into the cost function. Therefore, the three objective functions are converted into two objective functions, and the total cost function is obtained as shown in the *Equation (18)*.

Therefore, considering the minimum total cost and total time as the objective function, an optimisation model under the condition of uncertain network structure is constructed. The objective function of the model is composed of *Equation (15) and (18)*.

$$Z_5 = \sum_{k,k' \in K} \sum_{i,j \in V} (d_{ij} \cdot y_{ij}^k \cdot C_{sk} \cdot C_e + z_{ij}^r \cdot C_{kk'}^{re} \cdot C_e) \cdot D_{jc} \tag{17}$$

$$minZ_c' = min \sum_{k,k' \in K} \sum_{i,j \in V} d_{ij} \cdot y_{ij}^k \cdot \left(C_k + \frac{C_0}{v_{ij}^{sk}} + C_{sk} \cdot C_e\right) \cdot D_{jc} + z_{ij}^r \cdot (c_{kk'}^r + t_{kk'}^r C_0 + C_{kk'}^{re} \cdot C_e) \cdot D_{jc} + (1 - \varphi_c) \cdot D_{jc} \cdot C_c \tag{18}$$

Constraints

Equation (19) is flow balance constraint, *Equation (20), (21), (22)* are the time constraints. The supply-demand relationship constraint, that is, the demand cannot be greater than the supply, as shown in the *Equation (23)*. Multimodal transport network structure constraints, that is, the characteristic path length of the multimodal transport network shall not be less than 2[2], to ensure that the network can provide multimodal transport services, as shown in the *Equation (24)*.

Among them, the characteristic path length of the network is based on the complex network theory to construct the network topology structure under the background of the container cold chain multimodal transportation network. The characteristic path length L is expressed by the *Equation (25)*. Transportation and transshipment tasks cannot be dismantled constraints. The *Equation (26)* means that each road section can only choose one mode of transportation, that is, the non-dismantling constraints of transportation tasks; the *Equation (27)* means that the goods can only be transshipped once at the transshipment node, that is, the non-dismantling constraint of the transshipment task.

$$\sum_{k \in K} \sum_{i,j \in V} y_{ij}^k - \sum_{k \in K} \sum_{i,j \in V} y_{ji}^k = \begin{cases} 1, & i = O \\ -1, & i = D \\ 0, & otherwise \end{cases} \quad i,j \in V; k \in K \tag{19}$$

$$\sum_{k \in K} \sum_{i,j \in V} T_t + T_r \le SL_c \qquad \forall i,j \in V; k \in K \tag{20}$$

$$\sum_{k \in K} \sum_{i,j \in V} T_t + T_r \le T^U \qquad \forall i,j \in V; k \in K \tag{21}$$

$$\sum_{k \in K} \sum_{i,j \in V} T_t + T_r \ge T^D \qquad \forall i,j \in V; k \in K \tag{22}$$

$$\sum_{j \in V} D_{jc} \le \sum_{i \in V} O_{ic} \qquad \forall i,j \in V \tag{23}$$

$$\frac{2}{N(N-1)} \sum_{i,j \in V} \omega_{ij} \ge 2 \qquad \forall\, i,j \in V \tag{24}$$

$$L = \frac{2}{N(N-1)} \sum_{i,j \in V} \omega_{ij} \tag{25}$$

$$\sum_{k \in K} y_{ij}^k \le 1 \qquad \forall\, i,j \in V; k \in K \tag{26}$$

$$\sum_{k \in K} z_{ij}^k \le 1 \qquad \forall\, i,j \in V; k \in K \tag{27}$$

2.4 Solution approach

The routing problem investigated in this paper is a multi-objective problem. This research adopted the Gurobi solver to obtain the solution set of the routing scheme. *Figure 3* shows the general framework of the methodology. *Algorithm 1* describes the algorithm process.

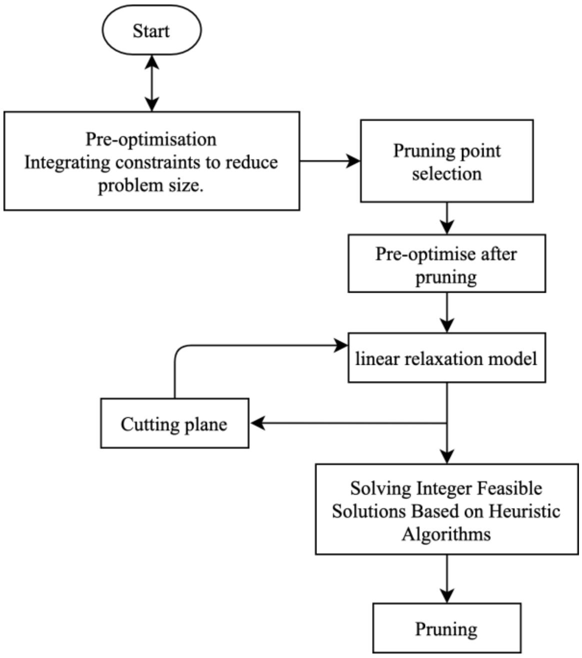

Figure 3 – Branch-and-cut algorithm flow in Gurobi

3. CASE STUDY

3.1 Data and parameter setting

The "Compilation of National Agricultural Cost and Income Data for 2019" (National Development & Commission, 2019) contained characteristic data of major agricultural products from various regions in China, including their primary production areas, yields, cost prices and profits. Taking into account the production area characteristics of agricultural products, the optimal design of multimodal transportation routes was conducted for the transportation of tomatoes from Xiangyang in Hubei province to Nantong in Jiangsu province, apples from Yantai in Shandong province to Jiaxing in Zhejiang province, and potatoes from Yulin in Shaanxi province to Shanghai. The transportation quantities for each product were 5 TEU for tomatoes, 10 TEU for apples and 15 TEU for potatoes. During transportation, it was required that the time from departure to arrival at the destination does not exceed 96 hours for apples, 168 hours for potatoes and 72 hours for tomatoes. Additionally, the transportation process complied with the requirements for refrigerated container transportation of agricultural products specified in the "Catering Cold Chain Logistics Service Specification" (WB/T 1054–2015). Table 1 shows the production cost data for the products from the "Compilation of National Agricultural Cost and Income Data for 2019" (20). The shelf life and quality deterioration data for the products were sourced from references [14, 41].

Table 1 – Values of relevant indicators for cold chain products [10,15,37]

Product	Shelf life (hour)	QRP (quality reduction point)	Cost of production (yuan/ton)
Apple	2880	75.0%	2890.6
Tomato	168	14.3%	866
Potato	5760	87.5%	976

The container cold chain transportation network consisted of 44 node cities. The attached datasets provide the transportation distances of roads, waterways and railways between each node. Among them, the waterway transportation distance between nodes came from the ship information network, the railway distance came from the train ticket website, and the road transportation distance came from the Baidu map. The data in *Tables 2* and *3* were derived from literature [39]. Containers in transit were 40ft refrigerated container boxes, loaded according to a load of 22 tons per container.

Table 2 – Values of transport-related indicators for multimodal transport [39]

	Road	Railway	Waterway
Transport speed (km/h)	47.51	35	12.5
Transport cost (CNY/km)	9	6.8	0.63
Carbon emission (kg/TEU · km)	16.126	10.296	13.024

Table 3 – Transit time and costs between multimodal transport modes [39]

	Cost (yuan/TEU)	Time (h/TEU)	Carbon emission (kg/TEU · km)
Road-railway	121	0.2	4.05
Waterway-road	132	0.4	4.25
Railway-waterway	165	0.37	4.65

An analysis of the structure of this multimodal network was conducted using Gephi to visualise the network topology, as shown in *Figure 4*. The darkness of the node colours corresponded to the degree value of the corresponding nodes. The darker the colour, the higher the degree value, and the darker and larger font sizes of node labels (city names) indicated higher node degree values, which indicates that the node had more connections with other nodes and was more important in the network. The degree values of the nodes gradually decreased from the centre to the periphery. Nodes located at the centre of the network had a higher importance in terms of centrality. When these nodes fail, the network's resilience and connectivity weaken, resulting in increased overall transportation costs and transportation time for the multimodal transportation organisation.

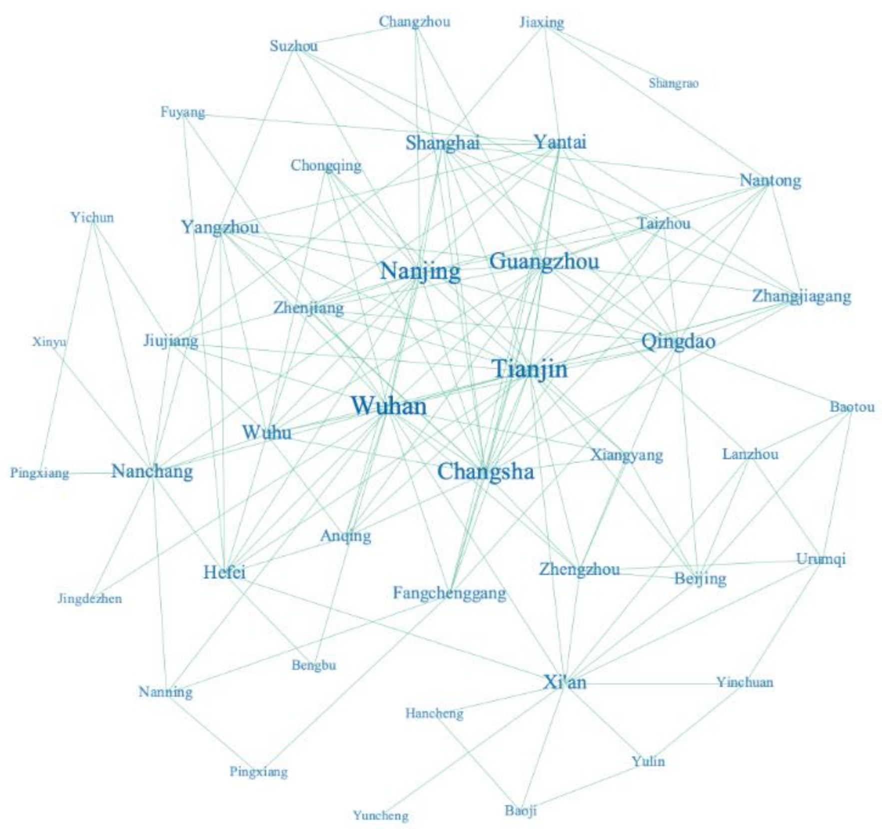

Figure 4 – Container cold chain multimodal transport network topology

3.2 Results

Gurobipy 9.1.2 solver was used to run linear programming solving code based on Python, which was on a MacBook Air configured with a 1.8 GHz Intel Core i5 processor and 8 GB 1600 MHz DDR3 memory. The solution yields a GAP=0, indicating an optimal solution. The obtained solution provides multimodal transportation routes and the associated costs.

The transportation routes and costs of each product are shown in *Figure 5* and *Table 4*.

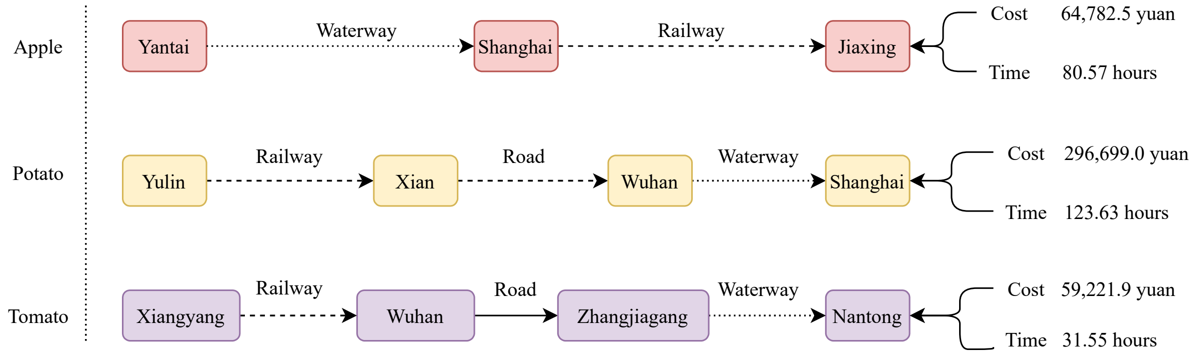

Figure 5 – Container cold chain multimodal transport scheme under the scenario of intact network structure

Table 4 – Results under the scenario of intact network structure (yuan)

Product	Total cost	Transport cost	Transshipment cost	Refrigeration cost	Carbon emission cost	Cargo loss cost
Apple	64,782.5	11,313.00	1,650.0	50,977.2	842.3	0.0
Potato	296,699.0	175,715.0	3,795.0	114,077.0	3,112.0	0.0
Tomato	59,221.9	44,822.0	1,265.0	9,620.0	519.3	2,995.6

In the transportation plan for apples, the total cost is 64,782.5 yuan, with an average cost of 6,478.2 yuan per TEU, and the transportation time from the origin to the destination is 80.57 hours. The transportation cost accounts for 17.46% of the total, the transfer cost accounts for 2.55%, refrigeration cost accounts for 78.69% and carbon emission cost accounts for 1.30%.

In the transportation plan for potatoes, the total cost is 296,699.0 yuan, with an average cost of 19,779.9 yuan per TEU, and the transportation time from the origin to the destination is 123.63 hours. The transportation cost accounts for 59.22% of the total, transfer cost accounts for 1.28%, refrigeration cost accounts for 38.45% and carbon emission cost accounts for 1.05%.

In the transportation plan for tomatoes, the total cost is 59,221.9 yuan, with an average cost of 11,844.4 yuan per TEU, and the transportation time from the origin to the destination is 31.55 hours.

The transportation cost accounts for 75.68% of the total, transfer cost accounts for 2.14%, refrigeration cost accounts for 16.24%, carbon emission cost accounts for 0.88% and loss cost accounts for 5.06%. Overall, refrigeration and transportation costs account for the largest proportion, reaching up to 97.67% (in the case of potato transportation). Therefore, reducing the expenses in these two areas can effectively lower the overall cost of the multimodal transportation plan. Since apples and potatoes have longer shelf lives with an acceptance rate of 1, there is no loss cost involved. However, tomatoes have a shorter shelf life with an acceptance rate of 80.17%, resulting in a loss cost of 2,995.6 yuan.

In the event that a multimodal network faces unforeseen natural disasters or significant public health incidents, resulting in the disruption of its operational capabilities, the ensuing circumstances can be categorised as a scenario characterised by an uncertain transportation network topology within the multimodal network. This research assumes that the multimodal network, specifically the container cold chain multimodal network, is subject to five uncertain attacks, resulting in the failure of five multimodal nodes. The multimodal path optimisation is then carried out on the network after removing the failed nodes. The failed nodes are determined by generating random numbers to simulate the random failure scenario of the nodes. Five nodes are randomly selected from nodes numbered 0 to 43 (if the selected nodes include the starting point of transportation, a new selection is made). When these nodes are unable to handle transportation operations after experiencing unforeseen events, the multimodal solution for the container cold chain needs to be replanned.

The random failure node numbers obtained using the random function in Python are 2, 7, 35, 11 and 20, which correspond to Wuhan, Wuhu, Baotou, Yangzhou and Anqing, respectively. The transportation distances between nodes for road, rail and waterway in the new container cold chain multimodal network are shown in the attached tables.

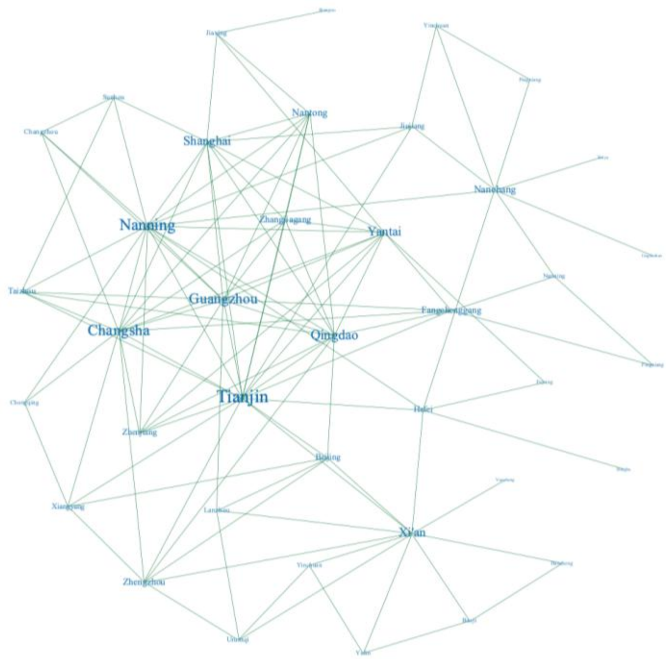

Figure 6 – Container cold chain multimodal transport network topology with 5 nodes failed

The new network topology is shown in *Figure 6*. A comparative analysis was conducted with the network structure diagram before the failure. The multimodal network experienced a decrease in the number of nodes and the density of connections. The key node Changsha replaced Wuhan as one of the top four key nodes. According to the conclusions drawn from the network characteristics analysis by (2), the characteristic path length and connectivity of the network decreased after the failure.

In the pursuit of solving optimisation problems for interconnection pathways on a new network, the resulting transport routes and costs for various scenarios under the context of uncertain attacks on the network structure are depicted in *Figure 7* and *Table 5*, respectively.

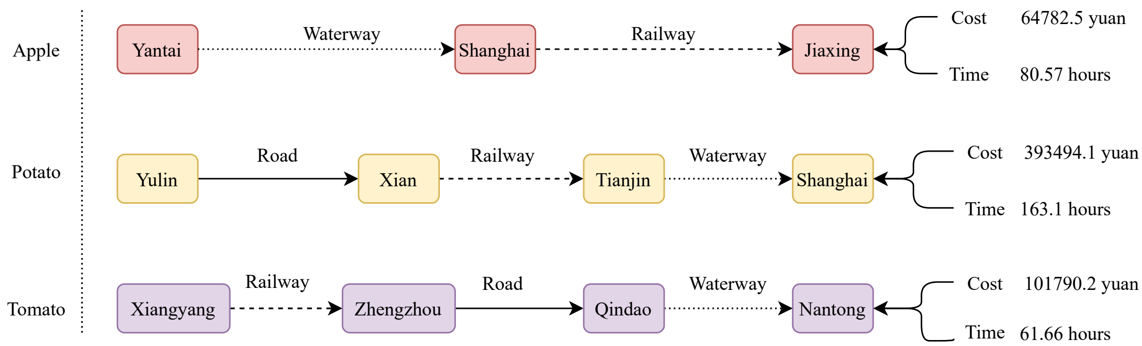

Figure 7 – Container cold chain multimodal transport scheme under the scenario of 5 nodes failed

Table 5 – Results under the scenario of 5 nodes failed (yuan)

Product	Total cost	Transport cost	Transshipment cost	Refrigeration cost	Carbon emission cost	Cargo loss cost
Apple	64,782.5	11,313.00	1,650.0	50,977.2	842.3	0.0
Potato	393,494.1	231,804.00	4,290.0	153,480.3	3,919.8	0.0
Tomato	101,790.2	55,331.00	1,265.0	19,594.1	701.3	24,899.8

In the case of apple transportation, the total cost amounts to 64,782.5 CNY, with an average cost of 6,478.25 CNY per TEU and a transit time from origin to destination of 80.57 hours. The cost breakdown reveals that transportation costs account for 17.46%, transshipment costs account for 2.55%, refrigeration costs constitute 78.69% and carbon emission costs represent 1.30%. Thus, the transportation of apples is unaffected by network node failures.

In the case of the potato transportation plan, the total cost reaches 393,494.1 CNY, with an average cost of 26,232.94 CNY per TEU, and a transit time from origin to destination of 163.1 hours. The distribution of costs shows that transportation cost accounts for 58.91%, transshipment cost accounts for 1.09%, refrigeration cost accounts for 39.00% and carbon emission cost accounts for 1.00%.

In the case of tomato transportation, the total cost amounts to 101,790.2 CNY, with an average cost of 20,358.03 CNY per TEU and a transit time from origin to destination of 61.66 hours. The cost allocation reveals that transportation expenses constitute 54.36%, transshipment costs 1.24%, refrigeration costs 19.25%, carbon emission costs 0.69% and quality loss costs 24.46%. Overall, refrigeration and transportation costs dominate, which reach as high as 97.91% (in the case of potato transportation). As apples and potatoes have a relatively long shelf life with an acceptance rate of 1, there are no quality loss costs. Conversely, tomatoes, with a shorter shelf life and an acceptance rate of 73.86%, accumulate quality loss costs of 24,899.8 CNY.

The failure of five nodes is generated randomly under uncertain circumstances. When these failure nodes do not intersect with the transportation of specific products, the transportation remains unaffected, as observed in the case of apple transportation, which is not affected by the network node failures. However, due to the failure of the Wuhan node, which served as a transshipment point in the original transportation for potatoes and tomatoes, its impact on the transportation of these products is substantial.

A comparative analysis between *Table 4* and *Table 5* reveals significant alterations in the transportation routes for potatoes and tomatoes due to node failures and changes in the network structure. The overall costs and time associated with multimodal transportation have increased. Specifically, for potato transportation, the transportation cost has risen by 96,795.1 CNY, representing a growth rate of 32.62%, and the transportation time has increased by 38.40 hours, reflecting a growth rate of 30.82%. Conversely, the transportation cost for tomatoes has increased by 42,568.3 CNY, indicating a growth rate of 71.88%, and the transportation time has extended by 30.10 hours, with a growth rate of 95.41%.

The multimodal transportation for containerised cold chain networks is affected by disruptions in scenarios where uncertainties result in node failures. These disruptions have a direct impact on transportation organisations, leading to higher costs and extended transit times. Therefore, maintaining a stable network structure is crucial in controlling multimodal transportation costs and reducing transit times.

3.3 Sensitivity analysis

The impact of nodes fail

The most significant impact on the network occurs when critical nodes fail. Wuhan serves as a key node connecting 22 network hub nodes, boasting the highest degree within the network, thus classifying it as an important node. Consequently, the failure of Wuhan has a substantial impact on multimodal transportation.

A comparison between *Figure 5* and *Figure 7* reveals that the transportation for apples remains unaffected since it does not involve any failed city multimodal hubs. Conversely, both potatoes and tomatoes are significantly affected due to the inclusion of the failed node, Wuhan, in their transportation plans, resulting in increased costs and transit times for these product categories. This demonstrates the critical role of Wuhan as a hub node in this multimodal transportation network.

Wuhan and Shanghai serve as important nodes. Therefore, when these city nodes fail due to deliberate attacks, they have a significant impact on network transportation. Hence, network connectivity and the reliability of transportation plans are more crucial in scenarios where nodes fail randomly than in scenarios where key nodes fail deliberately. When an important node, such as Wuhan, fails in the network, both multimodal transportation costs and time increase significantly.

The failure of key nodes has a significant impact on network performance. Most of the important nodes in this multimodal network are port cities, providing a range of transportation and transshipment services, including road, rail and water transportation. Therefore, when developing contingency plans for transportation node failures, it is essential to focus on contingency plans for these node functions.

From the analysis of network characteristics under node failure scenarios, the number of failed nodes increases, the network's potential for multimodal transportation decreases, as well as connectivity decreases.

In the context of the case study, as the number of failed nodes increases, the probability of nodes failing along the current transportation path also rises. If a node on the current multimodal route fails, multimodal carriers must re-plan their routes, leading to increased multimodal costs and transit times, significantly affecting the sustainability and cost-effectiveness of transportation.

The impact of railway transportation speed

In multimodal transportation, road transportation has the highest unit transportation cost per distance, while waterway transportation has the lowest cost. However, waterway transportation is constrained by natural conditions and is only feasible in regions with rivers, lakes and seas, especially those with harbours, particularly in large river basins. Railway transportation, on the other hand, falls between these two options in terms of cost and transportation speed. Moreover, China has established a comprehensive railway network, making railway transportation more competitive than the other two modes.

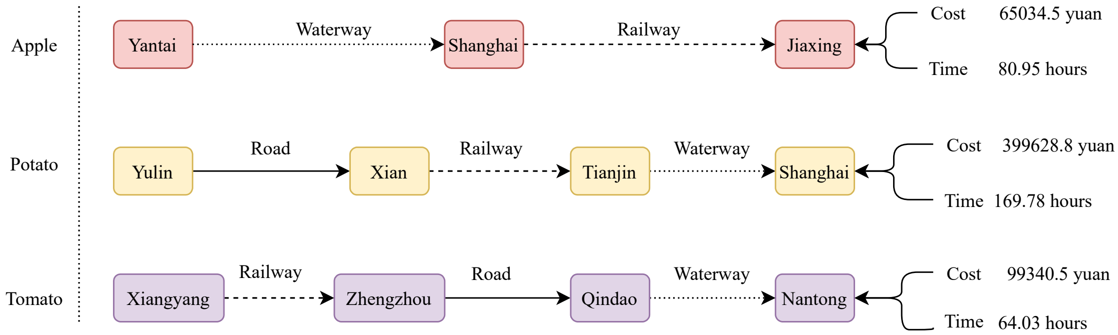

Figure 8 – Container cold chain multimodal transport scheme with 30 km/h railway speed

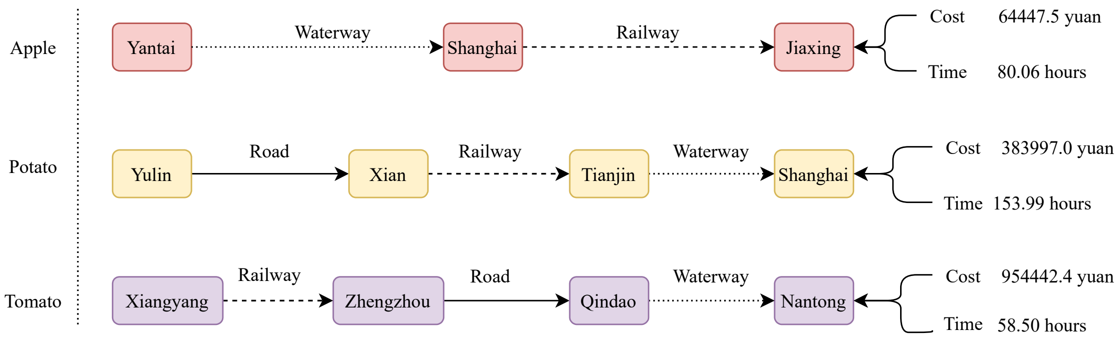

Figure 9 – Container cold chain multimodal transport scheme with 45 km/h railway speed

In this paper, a sensitivity analysis of railway transportation speed is conducted at 30 km/h, 35 km/h and 45 km/h [40]. When the railway transportation speed is set at 30 km/h or 45 km/h, and the network structure experiences the scenario of five nodes failing under uncertain attacks, the optimised transportation plans based on post-failure data for containerised cold chain multimodal transportation networks remain unchanged. However, the variation in railway transportation speed leads to changes in transportation times, subsequently affecting refrigeration costs. It is assumed that the unit transportation cost corresponding to different railway transportation speeds remains unchanged. A comparison with the results indicates that an increase in railway transportation speed effectively reduces the cost and time of the multimodal transportation plan.

According to the different types of trains, railway transport speed has multiple levels. Currently, the speed of railway freight transport in China, after acceleration, has reached over 90 km/h. In the future, upon obtaining the latest data on the speed, freight rates and other relevant information for road, rail and waterway transport, real case analyses can be conducted using the model and solution algorithm described in this chapter. Once the relationship between railway transport speed and freight rates is established, an optimisation analysis of multimodal transport routes under different railway speeds and freight rates can be performed. This will reveal how multimodal transport routes change under dynamic conditions, considering the combined impact of railway transport speed and freight rates. Additionally, the competitiveness of railway transport speed and pricing within multimodal transport will be analysed.

China has already established a comprehensive high-speed railway network [44], with speeds reaching up to 350 km/h. In the future, the inclusion of the high-speed railway network in the multimodal transport network can be considered. This will allow for an analysis of the optimisation of transport routes and operational organisation after the integration of the high-speed railway network into the multimodal transport network.

The impact of carbon tax

During the Two Sessions in March 2021, issues related to "carbon neutrality" were once again discussed and emphasised. As a key component of energy conservation and emissions reduction, initiatives such as promoting the development and use of electric vehicles and encouraging the growth of multimodal transportation were highlighted. In the future, China will introduce carbon taxes, and as carbon tax collection increases and standards are raised, it will drive society to adopt cleaner methods of organising transportation. Multimodal transportation, relative to single-mode transportation, offers characteristics such as environmental friendliness, efficiency and cost-effectiveness. In this research, a standard carbon tax rate of 6.5 CNY per ton was used. As carbon taxes increase, the initial impact is an increase in total costs. In the future, it may be considered how multimodal transportation with clean energy as the power source compares relative to those relying on petroleum-based fuels. This exploration could involve examining policies and approaches to promote the use of clean energy in multimodal transportation.

4. DISCUSSION AND CONCLUSION

This research has optimised the containerised cold chain transportation routes under conditions of network structure uncertainty caused by random node failures in a multimodal transportation network. Integrating the minimisation of carbon emissions into the overall cost objectives, a containerised cold chain multimodal transportation optimisation model was developed as a mixed-integer nonlinear programming problem. The model was transformed into a mixed-integer linear programming problem using linearisation techniques and solved using the Gurobi solver. To validate the model and algorithm, empirical data were used to analyse the multimodal transportation network under scenarios with an intact network and five randomly selected nodes experiencing failure. Comparative analysis of total cost and total time metrics showed that node failures increased both cost and time for transportation route plans. This emphasises the importance of emergency management following critical node failure, particularly in the face of increasing climate change, extreme weather events and natural disasters. The analysis of the composition of total costs indicates that transportation and refrigeration costs are the primary cost components in containerised cold chain transportation, while transfer costs and carbon emissions costs have minimal significance in transportation organisation optimisation. Short-shelf-life goods require special attention in terms of transportation process quality costs.

This research has two major theoretical contributions in extending the literature for the improved efficiency and resilience of container transportation. First, previous studies have mostly focused on optimising container transportation in the food cold chain [11] without explicitly incorporating uncertainties arising from network failures. To fill this gap, the proposed model has a novel comprehensive condition with 5 constraints associated with the network structure into the optimisation model that can better adapt to random failures of network nodes. This contribution is significant, as disruptions in the food cold chain can lead to substantial economic losses and compromise food safety. This research enhances the reliability and adaptability of container transportation systems in the face of uncertain network conditions. Second, the neglect of ad-hoc situations and route restrictions on unique requirements of perishable goods is another significant research gap. The past Covid-19 restrictions highlighted the vulnerabilities in the food cold chain transportation system [45], particularly in terms of sudden lockdowns, travel bans and border controls [46-49]. This research has addressed this gap by considering ad-hoc situations into the optimisation model, with its complex multimodal network and empirical analysis of real data on different characteristics of perishable goods, namely apples, tomatoes and potatoes. The research findings enable a more pragmatic and informed decision-making process when addressing the complexity resulting from unexpected circumstances and the distinctive needs associated with perishable goods.

The findings of this research also have practical implications and potential impacts on the logistics industry. By integrating network structure uncertainty and ad-hoc situations into the optimisation model, our research enables decision-makers to make better-informed decisions when planning container transportation routes, which can lead to improved efficiency, reduced costs and enhanced supply chain resilience. The focus on fruits and vegetables transportation offers practical solutions that can directly benefit stakeholders involved in the transportation of these perishable goods.

Nevertheless, certain limitations need to be considered in this research. The optimisation model and findings are based on specific assumptions and scenarios. We have made certain assumptions about the network structure, ad-hoc situations and the perishable goods being transported in China. These assumptions should be further investigated to fully capture the complexity and variability in real-world scenarios, such as the transfer efficiency between two modes [50]. Second, the availability and accuracy of data used in the study is another limitation. The quality and availability of data can impact the accuracy and reliability of the optimisation model and results. We have utilised available data sources and made necessary assumptions for data gaps, but there may still be limitations in terms of data precision and representativeness.

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