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Importance-based risk evaluation methodology in transportation cyber-physical systems

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Abstract Cyber-physical systems (CPSs) play a crucial role in modern transportation, particularly in transportation cyber-physical systems (TCPSs) for emergency supply logistics. By utilizing real-time data collection, analysis, and communication technologies, TCPS improves the efficiency, safety, and reliability of emergency supply transportation systems. However, existing research often overlooks the dynamic nature of the transportation environment and the complexities of joint emergency supply transportation amid uncertainty. The risk factors for both the physical and cyber layers are inadequately addressed. Consequently, assessing the risks associated with transporting emergency materials within CPS frameworks remains a significant challenge. This study proposes a risk assessment model based on TCPS to analyze the risks associated with transporting emergency supplies via various transportation modes. Initially, a comprehensive analysis of risk factors spanning both the cyber and physical layers within the TCPS is conducted. A risk assessment model is subsequently developed by considering transportation time costs, expenses, and delays. A risk area is then introduced to simulate the impact of recurrent emergency events on emergency supply transportation. Finally, we simulate emergency supply transportation scenarios to facilitate effective risk evaluation.

Keywords risk, importance, cost, cyber-physical system

1 Introduction

1.1 Background

In the past two decades, the frequency of meteorological disasters, such as earthquakes, floods, and storms, as well as large-scale epidemics, such as coronavirus disease 2019, has steadily increased. Data show that between 2000 and 2020, these disasters resulted in global economic losses exceeding 5 trillion dollars (Kundu et al., 2022). The rise in these emergencies has not only caused significant economic losses but also resulted in substantial human casualties. Therefore, it is crucial to address the challenge of enhancing emergency response capabilities and efficiency. The transportation of emergency supplies plays a crucial role in rescue operations (Wang et al., 2022). After emergencies such as earthquakes, floods, or hurricanes, affected regions often have an urgent need for essential provisions, such as food, water, medicine, medical equipment, and other life-saving necessities. The utilization of cyber-physical systems (CPSs) for supply transportation can facilitate the prompt delivery of emergency supplies (Feng and Ye, 2021). Thus, improving the transportation method of emergency materials in a CPS is beneficial for disaster management.

In recent years, CPSs, which integrate advanced computing, communication technologies, and physical components, have been widely applied in various domains (Yang et al., 2021; Wu and Li, 2021). The transportation cyber-physical system (TCPS) enables the provision of real-time data and information, enabling rapid response to emergencies and adjustment of transportation strategies. By implementing TCPS, the transportation of emergency supplies can achieve increased efficiency, safety, and control. However, due to the

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inherent unpredictability and uncertainty associated with emergency supplies, CPS-based transportation systems may not always be reliable (Choi et al., 2016). This unreliability can significantly impede the transportation of emergency supplies, especially when the TCPS fails to collect and transmit data effectively from the transportation system. As a result, it is essential to assess the risks associated with transporting emergency supplies to effectively organize transportation activities.

1.2 Literature review

This section reviews the research status of material transportation strategies and risk assessment methods in TCPS.

In terms of material transportation strategy, the distribution and supply of emergency supplies after a disaster are critical for relief and recovery efforts, given the unpredictable and uncertain nature of disasters (Sheu, 2014; Loree and Aros-Vera, 2018; Li et al., 2022; Dui et al., 2023). Wang and Nie (2023) conducted a study on the transportation of emergency supplies following hurricanes and proposed a path-based location-inventory-routing model to increase the efficiency of last-mile distribution. Kawase and Iryo (2023) utilized dynamic stochastic optimization to investigate the distribution strategy of emergency supplies in a multilevel network, aiming to rapidly supply and meet the demand for emergency supplies in disaster areas. Xiong and Xue (2023) analyzed the feasibility of blockchain technology to improve information sharing and collaborative transportation in the emergency supply transportation process while considering information uncertainty. Dui et al. (2024a) proposed a real-time control strategy based on TCPS to improve system performance. Fan et al. (2022) proposed a deep Q-network approach to address the emergency supply distribution problem, taking into account the degree of damage and characteristics of the disaster area. Fan et al. (2023) proposed an optimization method that considers the nonlinear energy consumption of buses with dynamic loads to solve multi-route electric vehicle scheduling. Existing research on emergency supply transport allocation has established complex networks and employed location–inventory distribution methods. However, the joint scheduling of multiple transport vehicles with limited resources can further enhance emergency material distribution strategies.

In terms of risk assessment methods, risk is commonly defined as the likelihood of an event occurring and the potential severity of the resulting losses. This is often measured through the combination of likelihood and consequence (Hosseini et al., 2020). Risk assessment approaches can generally be classified as qualitative, quantitative, or integrated methods (Abimbola et al., 2016; Zhang et al., 2022; Tao et al., 2022; Huang et al., 2020). In recent years, there has been a significant focus

on conducting risk analysis in various systems. For example, Zeng et al. (2021) applied percolation theory to develop a framework for evaluating health management in transportation systems. This framework aims to analyze uncertainty risks within the system and enhance its reliability. Huang et al. (2023) conducted a comprehensive literature review on maritime transportation networks, providing a detailed comparative analysis of risk assessment methodologies in this field. Dui et al. (2024b) focused on the physical layer of the TCPS and analyzed different types of cascading failures of TCPS. Adamov et al. (2021) specifically concentrated on the transportation of hazardous materials and proposed a risk assessment framework tailored to such scenarios. Szacillo et al. (2021) analyzed the causes of failures in railroad cargo transportation via statistical data on railroad accidents, quantified accident probabilities and assessed the associated risks. Chen et al. (2019) examined the factors influencing risk propagation in emergency logistics through the SIS communication model and proposed strategies to identify and mitigate risks in emergency logistics. Dui et al. (2024c) summarized importance-based risk assessment and optimization strategies for complex systems. Bai et al. (2021) proposed an improved grid risk reduction measure based on node importance for grid systems. Although current systematic risk assessment methodologies rely on subjective frameworks, there is a need for enhanced risk assessment methodologies that objectively account for the significance of nodes within the transport network.

1.3 Motivation and contribution

Although numerous scholars have extensively studied the transportation and distribution of emergency supplies, the existing research often focuses on a single transportation route and adopts subjective tendency risk assessment methods. This approach fails to consider the dynamic and uncertain nature of the transportation environment, especially in relation to joint transportation operations. Additionally, there is a lack of emphasis on the time-varying factors and inherent uncertainties in transportation logistics, as well as the distinct risk characteristics associated with both the physical and cyber layers of the TCPS, particularly in emergency supply transportation.

To address the problem of joint transportation for emergency supplies, this paper proposes a modeling framework for the transportation system within the TCPS. First, it introduces an importance measure for paths and nodes that considers the differences in emergency supply types and their respective levels of importance. Next, a risk assessment model is developed that incorporates the importance measure of paths and nodes in accurately assessing risk costs associated with delays. Finally, the transportation costs, transportation times, and risks for the four transportation scenarios are established and

calculated. The results demonstrate that transportation time and risk values are lower in the joint transportation at risk scenario than in the other scenarios.

1.4 Structure

The remaining sections of this paper are structured as follows. Section 2 provides an introduction to the TCPS and defines the problem. Section 3 presents the proposed importance measures for the two layers of the TCPS. Section 4 outlines the methodology for risk evaluation within the TCPS. Section 5 uses a specific affected area in China as an example to model and simulate the proposed methods. Section 6 concludes the paper and outlines avenues for future research.

2 Description of TCPS and problem posing

The TCPS represents a sophisticated integration of networked, intelligent, and digital systems within the transportation domain (Henshaw, 2018). It operates on a large scale, with a complex interconnection of information and transportation networks. The TCPS consists of three core components: the physical, cyber, and application layers, as depicted in Fig. 1.

Each node within the TCPS has significant tangible

physical importance. The nodes in the physical transportation network are responsible for material transportation, whereas the nodes in the cyber layer handle information sensing and transmission. Sensor nodes, communication nodes, and control nodes in the cyber layer seamlessly integrate into the shared infrastructure of the physical system. In the physical layer, sensor nodes, roadside units (RSUs), and remote sensing technology enable the collection of traffic system data, including vehicle, road, and environmental information. Moreover, data transmission is achieved through wireless technology via communication nodes in the cyber layer. In the application layer, the cloud computing data processing center uses robust computing power to process the collected traffic system data and generate real-time and effective control information. This information is then promptly relayed back to the physical layer through control nodes.

The TCPS facilitates a comprehensive perception of the transportation network by integrating transportation data and efficiently coordinating computing and transportation resources. By employing V2V, V2R, or V2I communication technologies, vehicles within the TCPS can seamlessly exchange information. This enables real-time data transmission and exchange during emergency supply transportation, offering decision support for optimal transportation routes and modes. Consequently, TCPS enhances transportation efficiency, mitigates risks, and

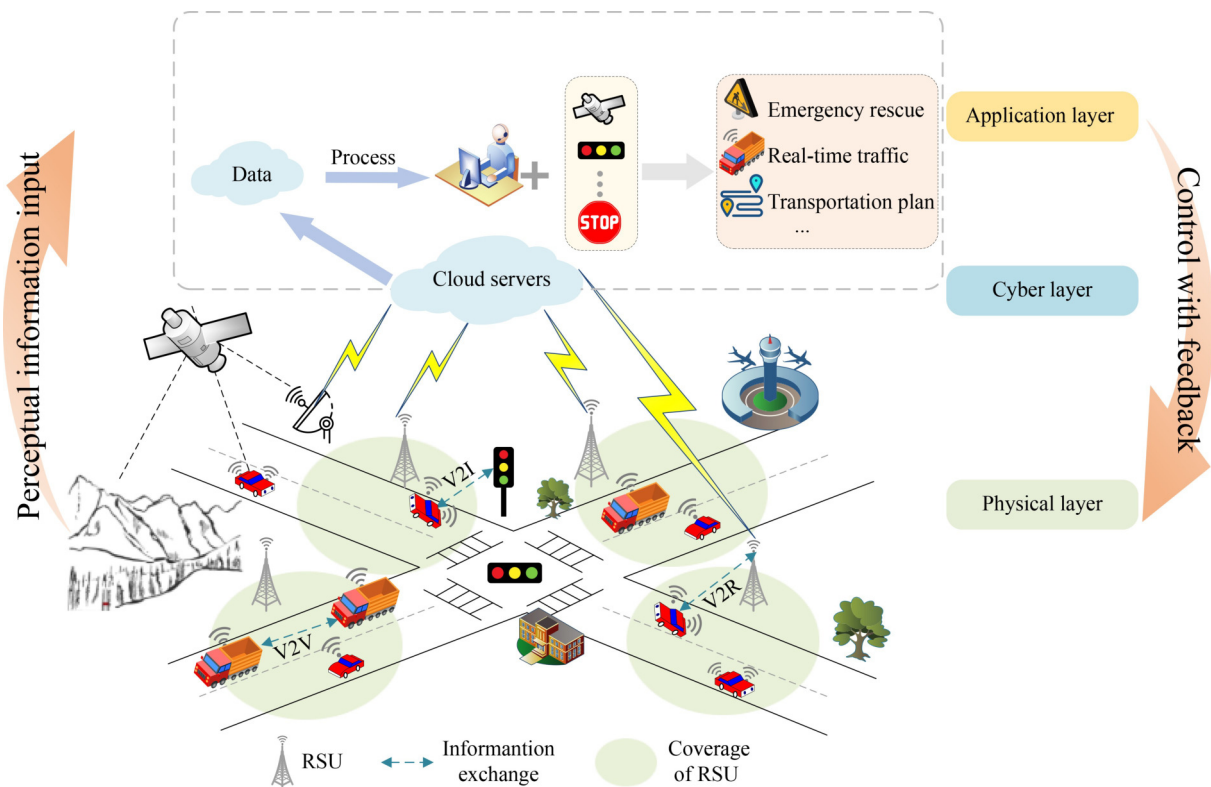


Fig. 1 The transportation cyber-physical system.

fulfills material demands during emergencies.

The emergency supply transportation network consists of supply nodes (emergency supply storehouses), demand nodes (affected areas), and hub nodes (e.g., airports), as depicted in Fig. 2. Supply nodes provide emergency supplies to affected areas, whereas demand nodes represent areas in need of various emergency supplies. Hub nodes serve as pivotal points for intermodal transportation to facilitate efficient supply movement. During emergencies, road damage or area closures may disrupt normal vehicle travel. Hub nodes adapt transportation modes on the basis of system conditions to increase emergency supply transportation efficiency. This paper employs graph theory to describe the topology of emergency supply transportation networks. The abstract digraph $G(V, E)$ represents the emergency supply transportation network. $V = \{v_i\}$ is a set of nodes, where V_s represents the supply node, V_d represents the demand node, and V_h represents the hub node. $E = \{e_{ij}\}$ is a set of edges, representing all the paths in the system. M represents the set of transportation modes, m and l represent the different transportation modes, and $m, l \in M$.

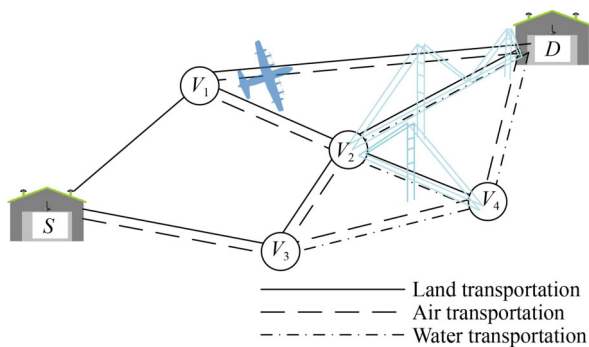


Fig. 2 Emergency supply transportation network.

3 Risk factors and importance measures for the two layers of the TCPS

The TCPS integrates traditional transportation systems with information and communication technologies to enhance transportation management and control efficiency, ultimately promoting reliability, safety, and sustainability. This section begins by examining the risks associated with the TCPS, specifically focusing on the emergency supply transportation system and the cyber layer. Furthermore, node attributes, supply importance measures, and information importance measures are introduced to determine the significance of each node. Finally, a tailored risk assessment model is proposed, which is specifically designed for the emergency supply transportation system within the CPS framework.

3.1 Physical layer and cyber layer risk factors

3.1.1 Physical layer risk factors

Sudden events, such as earthquakes, can result in infrastructure breakdowns and casualties, leading to disruptions in transportation networks. The consequences of these disasters include road closures, airport shutdowns, and suspensions of public transportation, all of which cause delays in emergency supply transportation. Additionally, adverse weather conditions such as heavy rain, snowstorms, and high winds can threaten vehicles and increase vehicle safety, further impacting transportation efficiency and safety. However, the TCPS has the ability to address these challenges by using sensors and remote sensing technology to collect timely weather and environmental data. By integrating this comprehensive information, the TCPS facilitates informed decision-making for emergency supply transportation.

3.1.2 Cyber layer risk factors

The TCPS obtains timely information about the transportation network (e.g., vehicle speed, congestion conditions, and road traffic) and environmental factors (e.g., weather and temperature) through sensing and communication nodes. However, unforeseen events can disrupt these nodes, particularly the sensing nodes in the physical layer and the communication nodes in the cyber layer. Physical attacks or equipment aging may lead to equipment or line failures, resulting in data corruption or transmission disruptions. Devices deployed in unattended environments with limited communication and processing capabilities are especially vulnerable. Any damage to sensing and communication nodes impedes information transmission, consequently hindering the application layer's ability to access timely transportation network information and make prompt decisions regarding emergency supply transportation.

3.2 Importance measures of supply and information

Node importance is a critical metric for evaluating the significance of individual nodes in a network and guiding resource allocation, decision-making, and optimization strategies. Topology-based measures of node importance, such as degree centrality and betweenness centrality, focus primarily on node connectivity and are relatively easy to compute. However, the attributes associated with each node greatly impact its importance. Evaluation methods that rely solely on topology may overlook node attributes, resulting in inaccurate assessments.

The cyber layer of the TCPS consists of sensor nodes, communication nodes, and control nodes that are tightly integrated into the shared infrastructure of the physical

system. This integration gives nodes within the transportation network based on CPSs a nuanced significance beyond topology-based assessments. In this section, we introduce supply importance and information importance measures to comprehensively evaluate the significance of edges and nodes. The use of these comprehensive metrics improves our understanding of individual node importance within the system and informs decision-making processes.

3.2.1 Importance measure of paths

Generally, network topology is a valuable tool for assessing edge importance. For example, edges with higher centrality indicate greater connectivity to neighboring edges within the network. Consequently, if such an edge is disrupted due to an unexpected event, it can significantly impact adjacent edges, thus affecting the entire transportation network. By evaluating pathway importance, we can identify different transportation routes for emergency supplies to increase supply transportation efficiency. This provides valuable insights for rational emergency supply transportation planning. This paper adopts a path supply importance measure and path information importance measure to comprehensively assess pathway importance within an emergency transportation system.

(a) Path supply importance measure

The importance of supplies in an emergency supply transportation network is defined as the total importance of supplies passing through a specific path per unit time and unit distance, denoted by y_r ($r = 1, 2$).

The transportation tasks in the network can be categorized into two types on the basis of the transported materials: general supplies (with an importance measure of y_1) and important supplies (with an importance measure of y_2), as shown in Table 1.

General supplies, with an importance measure of y_1 , are of slightly less urgency but remain critical to the emergency effort. These supplies include energy supplies (such as fuel and electricity), maintenance supplies, and rescue equipment, among others. The general supplies are primarily transported by land. On the other hand, important supplies, with an importance measure of y_2 , are the highest priority in emergency situations. These supplies are directly related to life safety and rescue operations, including survival supplies (food, water, etc.) and first aid

Table 1 Comparison of supply importance measures

Supply importance measure	Physical meaning
General supplies (y_1)	Maintenance supply
	Rescue equipment
	Energy supply (electricity, fuel, etc.)
Important supplies (y_2)	Survival supply (food, water, etc.)
	First aid supply

supplies (medical supplies, etc.). The supply of these materials should be given the utmost priority. The transportation of these supplies typically utilizes joint or single transportation, depending on the specific circumstances.

If there are c paths involved in the transportation process of materials within the transportation network, there are K instances of material transfer between node v_i and node v_j within time t , with the importance of the k -th transported material denoted as y_r^k and the quantity of transported material as z^k . Additionally, since each path in the network is not identical, let φ_k ($0.8 \leq \varphi_k \leq 1.2$) represent the road obstruction coefficient of path k . When the path is a regular road, $\varphi_k = 1$, indicating smooth and easy passage. If $\varphi_k > 1$, the road conditions are worse, and transportation on such paths requires more vigilance due to environmental uncertainties, which can affect the importance of the transported materials. The importance measure V_k of each transportation instance should consider both the material importance measure and the quantity of materials, which is defined as follows:

$$V_k = \varphi_k (\delta \times z^k + \varepsilon \times y_r^k), \quad (1)$$

where δ and ε represent the weights of the quantity of supplies and the importance measure of supplies, respectively. $\delta, \varepsilon \in [0, 1]$, and $\delta + \varepsilon = 1$. The path importance measure of the logistic path e_{ij} in the emergency supply transportation network is defined as follows:

$$G_{e_{ij}} = \frac{\sum_{k=1}^{k=K} V_k}{t \times d_{ij}}, \quad (2)$$

where t represents the transportation time and where d_{ij} represents the distance.

The path supply importance measure is defined as the importance of paths with material transportation functions to the supply transportation network. The path supply importance measure of the e_{ij} path is given by:

$$H_{e_{ij}} = \frac{\sum_{k=1}^{k=K} V_k}{t \times d_{ij}} \Bigg/ \sum_{n=1}^{n=c} \frac{\sum_{k=1}^{k=K} V_k}{t \times d_{ij}}, \quad (3)$$

where c represents the number of paths involved in the transportation process of materials within the transportation network.

(b) Path information importance measure

In the TCPS, the sensing information and control information are transmitted at the cyber layer. The path information importance measure of the emergency supply

transportation network is defined as the total importance measure of information passing through a specific path, measured in units of time and distance. It is denoted by θ_i ($i = 1, 2$). In this paper, the information is divided into two categories: general information and important information, as shown in Table 2.

Table 2 Comparison of information importance measures

Information importance measure	Physical meaning
General information (θ_1)	Perceptual information (Road conditions, weather conditions, etc.)
Important information (θ_2)	Interaction and Control information (Transportation plan, risk assessment information, etc.)

The importance measure of the k -th information transfer is denoted as θ_i^k , and the transmission distance is d_{ij} . In the emergency supply transportation network, the information importance on the e_{ij} -th path among the n paths is defined as follows:

$$S_{e_{ij}} = \sum_{k=1}^{k=K} \frac{\theta_i^k}{t \times d_{ij}} \tag{4}$$

The path information importance measure is defined as the importance of paths with information transfer functions to the supply transportation network. The importance measure of the information for the specific path in the transportation network, represented by the e_{ij} path, is given by:

$$B_{e_{ij}} = \frac{\sum_{k=1}^{k=K} \frac{\theta_i^k}{t \times d_{ij}}}{\sum_{i=1}^{i=n} \sum_{k=1}^{k=K} \frac{\theta_i^k}{t \times d_{ij}}}, \tag{5}$$

where n represents the number of paths in the network that are involved in the information transfer process.

3.2.2 Importance measure of nodes

The node importance measure in the emergency supply transportation system reflects the level of significance that each node holds in the network's functionality. A higher node importance measure signifies the greater importance of that node within the system. The failure or disruption of a node with a higher importance measure would have a more pronounced effect on overall network operations. In transportation systems, nodes can represent supply origination and destination points, as well as cargo turnover stations. Calculating node importance measures helps identify pivotal nodes crucial for system stability and effectiveness. These measures can be used to optimize the network, enhancing efficiency and resilience.

In the emergency supply transportation system, information exchange and supply transportation between nodes are facilitated by interconnected edges. The importance measure of a node increases with its connectivity to a greater number of edges, indicating its significance within the network. The supply importance measure of a node is defined as the sum of the supply importance measures of each path connected to it. Assuming that there is an equipment transportation relationship between v_i and v_j , the supply importance measure of v_i can be defined as follows:

$$I_i^G = \sum_{j=1}^{j=n} H_{e_{ij}} \tag{6}$$

Similarly, the information importance measure of a node is defined as the sum of the information importance measure of each path connected to that node. If there are k nodes in the network that have information transmission relationships with v_i , the information importance measure of v_i is defined as:

$$I_i^M = \sum_{j=1}^{j=k} B_{e_{ij}} \tag{7}$$

The comprehensive importance measure of v_i can be obtained by integrating the importance measure of the supply and information of node v_i , which is defined as:

$$I_i^C = \alpha \times I_i^G + \beta \times I_i^M, \tag{8}$$

where α and β represent the weights assigned to the supply importance measure and information importance measure of node v_i , respectively. Both α and β are between 0 and 1, and $\alpha + \beta = 1$.

4 Risk evaluation methodology in the TCPS

Drawing upon the concept of risk and prior research, it is clear that system risk is correlated with both the probability of system failure and the associated costs. This paper uses the expected failure cost as a metric for quantifying risk, which combines the probability of failure with the associated costs. To achieve this objective, a risk assessment model is developed that focuses on the costs involved in the process of transporting emergency supplies.

The failure risk of the emergency supply transportation system can be defined as follows:

$$Risk(t) = E(F) = \mu \times F(t), \tag{9}$$

where $E(F)$ represents the expected cost of a system failure, μ is an input parameter that represents the probability of a task failure, and $F(t)$ is the total cost of transporta-

tion. All types of costs in the transportation process include transportation time costs, transportation expense costs, and delay costs. The following sections expand on several types of costs.

The transportation time (T_y) in an emergency supply transportation system consists of two components: the on-route transportation time (T_{ij}^m) and the transfer time (T_i^{ml}).

(a) On-route transportation time T_{ij}^m

The on-route transportation time represents the total time for the material to travel from the supply node to the demand node. It is influenced primarily by the transportation distance and mode. In this study, the average transportation time t_{ij}^m is calculated by the transportation distance d_{ij}^m and the average transportation speed s_{ij}^m between nodes v_i and v_j via different transportation modes, which is defined as follows:

$$t_{ij}^m = \frac{d_{ij}^m}{s_{ij}^m}, \quad (10)$$

where d_{ij}^m represents the transportation distance between v_i and v_j via transportation mode m , and s_{ij}^m represents the average transportation speed.

The expression for the on-route transportation time can be defined as:

$$T_{ij}^m = \sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m t_{ij}^m, \quad (11)$$

where p_{ij}^m is a 0–1 variable that represents whether the materials are transported by mode m from v_i to v_j . If mode m is adopted, $p_{ij}^m = 1$. Otherwise, $p_{ij}^m = 0$.

(b) Transfer time T_i^{ml}

The transfer time refers to the time spent on cargo handling and transferring at the hub nodes. It is influenced by the transportation mode and the quantity of supplies being transported. The expression for the transfer time is defined as:

$$T_i^{ml} = \sum_{i \in V_h} \sum_{l \in M} \sum_{m \in M} q_i^{ml} t_i^{ml}, \quad (12)$$

where t_i^{ml} represents the time to switch from transport mode m to transport mode l , and q_i^{ml} is a 0–1 variable. When the transported material is converted from transport mode m to transport mode l at node v_i , $q_i^{ml} = 1$. Otherwise, $q_i^{ml} = 0$.

The transportation time cost C_1 can be calculated by:

$$C_1 = \gamma (T_{ij}^m + T_i^{ml}), \quad (13)$$

where γ is an input parameter and represents the cost per unit of time.

The transportation expense is an important factor in selecting a transportation mode. The expense cost component of the transportation network (C_y) consists of two parts: the on-route transportation expense (C_{ij}^m) and the

transfer expense (c_i^{ml}).

(c) On-route transportation expense C_{ij}^m

The transportation expense incurred during the transport of supplies from the supply node to the demand node is referred to as the on-route transportation expense. It is primarily determined by the transportation distance between nodes v_i and v_j for different transportation modes, as well as the varying unit expenses associated with different transport vehicles. The formula for calculating the on-route transportation expense is defined as follows:

$$C_{ij}^m = \sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m c_{ij}^m z_{ij}^m d_{ij}^m, \quad (14)$$

where c_{ij}^m , z_{ij}^m , and d_{ij}^m represent the unit transportation cost, the number of supplies and the transportation distance when mode transportation is used m , respectively.

(d) Transfer expense C_i^{ml}

The cost incurred during the process of switching transportation modes, known as the transfer cost, includes expenses such as handling and transshipment fees. The transfer expense is influenced by the quantity of supplies being transferred. The formula for calculating the transfer expense is defined as follows:

$$C_i^{ml} = \sum_{i \in V_h} \sum_{l \in M} \sum_{m \in M} q_i^{ml} c_i^{ml} z_i^{ml}, \quad (15)$$

where c_i^{ml} and z_i^{ml} represent the unit transfer cost and the number of supplies needed to switch from transport mode m to transport mode l in v_i , respectively.

The delay cost is the additional cost because supplies do not reach their destination on time. The risks associated with the transportation of emergency supplies and the transmission of information in the TCPS are discussed in Section 3.1. These existential risks may result in transport delays. Considering the characteristics of the TCPS, the delay cost mainly consists of two parts: the physical layer and the cyber layer. The cost of delay due to transportation delay is defined as follows:

$$EC = EC_p + EC_c = \sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m z_{ij}^m d_{ij}^m (ec_p^m + ec_c^m), \quad (16)$$

where ec_p^m and ec_c^m represent the delay cost of the physical layer and the delay cost of the cyber layer, respectively, when the transportation mode m is used.

Moreover, the emergency supplies transported by joint transportation need to be unloaded and reloaded at the hub nodes. Owing to the sudden and unpredictable nature of contingencies, they may pose a threat to cargo changes at the hub node v_i , resulting in materials not being delivered to the demand node in time. The greater the comprehensive importance I_i^C of the hub node v_i is, the greater the impact of the contingency on it. Considering the risks in

the process of combined transportation, the delay cost is adjusted by

$$EC = EC_p + EC_c + EC_i$$

$$= \sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m z_{ij}^m d_{ij}^m (ec_p^m + ec_c^m) + \sum_{i \in V_h} \sum_{m \in M} I_i^C q_i^m z_i^m ec_i^m, \tag{17}$$

where ec_i^{ml} represents the delay cost when transport mode m is converted to transport mode l .

According to the above analysis, the total transportation cost mainly includes the transportation time cost, transportation expense cost and delay cost. Therefore, the total cost can be calculated by

$$F = \sum_{k=1}^3 F_k, \tag{18}$$

$$F_1 = \gamma(T_{ij}^m + T_i^{ml}) = \gamma \left(\sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m t_{ij}^m + \sum_{i \in V} \sum_{l \in M} \sum_{m \in M} q_i^m t_i^{ml} \right), \tag{19}$$

$$F_2 = C_{ij}^m + C_i^{mi} = \sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m c_{ij}^m z_{ij}^m d_{ij}^m + \sum_{i \in V_h} \sum_{m \in M} \sum_{l \in M} q_i^m c_i^{ml} z_i^{ml}, \tag{20}$$

$$F_3 = EC = \sum_{i \in V} \sum_{j \in V} \sum_{m \in M} p_{ij}^m z_{ij}^m d_{ij}^m (ec_p^m + ec_c^m) + \sum_{i \in V_h} \sum_{m \in M} I_i^C q_i^m z_i^m ec_i^m. \tag{21}$$

5 Case study

This section focuses on modeling and simulating the transportation process within the emergency supply transportation system. The simulations include scenarios involving truck transportation and joint truck–aircraft transportation. These simulations are conducted via AnyLogic simulation software. This study focuses on a disaster area in China and simulates the transportation of emergency supplies on the basis of TCPS principles. The simulation scenario consists of three supply nodes, five demand nodes, and one hub node (airport).

The simulation includes the following seven agents, as shown in Table 3.


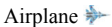

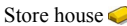
Emergency supplies are crucial for supporting rescue operations. In this simulation, the transportation network for emergency supplies assumes three types of materials: energy supply, survival supply, and first aid supply. Each type of material is stored in one of three designated storehouses, with three trucks assigned to each storehouse for distribution. Additionally, the hub node is equipped with

two transport planes capable of joint transportation with trucks. Each aircraft can transport only one item at a time.

Trucks and planes are the functional entities in the simulation and are responsible for transporting supplies from the storehouses to the affected area. The transportation process is represented via a state diagram, which depicts the process of transporting emergency supplies during joint transportation (Fig. 3).

In the joint transportation scenario, when the demand node (disaster area) requires supplies, the order is assessed to determine if it should be transported solely by trucks or through a combination of trucks and planes. If the order is designated for truck transportation only, the truck receives the order and proceeds directly to the demand area along the designated GIS route. In case of joint transportation involving both trucks and aircraft, the order is transported by truck to the airport, where the remaining transportation tasks are fulfilled by the aircraft. It is assumed that although the truck will pass through the

Table 3 Agent compositions

Agents	Illustration
Truck 	Truck, used for transportation
Airplane 	Transport aircraft, used for long-distance and important supplies transportation
Targets 	Affected areas, i.e., demand node
Store house 	Storehouse, i.e., supply node
Energy supply	Electricity, fuel, etc.
First aid supply	Medical supply, etc.
Survival supply	Food, water, etc.

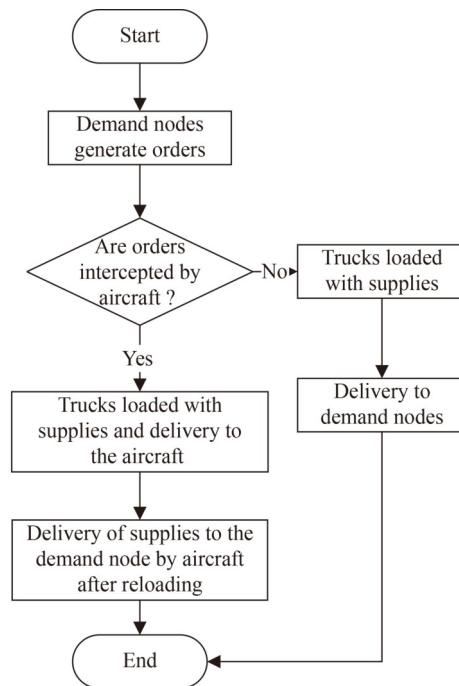


Fig. 3 Transportation vehicle state diagram.

risk area and be affected by it, it will ultimately arrive at the airport. Upon delivery to the demand node, the materials are unloaded, and the transport vehicle returns to the local storehouse for the next assignment.

To model the inventory of the three materials, the simulation uses the process modeling library within the software. This modeling process is presented in the form of a flowchart, effectively illustrating the operational status of production lines, service processes, and logistics flows, thereby enhancing the realism and intuitiveness of the simulation. The main modules of the process modeling library used in the simulation are detailed in Table 4.

The modeling of the process for truck transportation is

Table 4 Main modules of the process modeling library

Modules	Illustration
resourceTask	Starting point of the process diagram, representing the entry of resource demand tasks into the process modeling library
queue	Queue, i.e., a buffer area for the agent before entering the next module
resourcePool	Resource pool, i.e., a storage location for resources, representing trucks and aircraft to transport emergency supplies in this model
seize	Retrieve resources from the resource pool, specifically fetching a transportation vehicle
release	Release the resources, specifically releasing the occupation of the transportation vehicle
wait	Waiting time in simulation
timeMeasureStart	
timeMeasureEnd	Measure the time spent
selectOutput	Divert incoming agents and choose different transportation mode

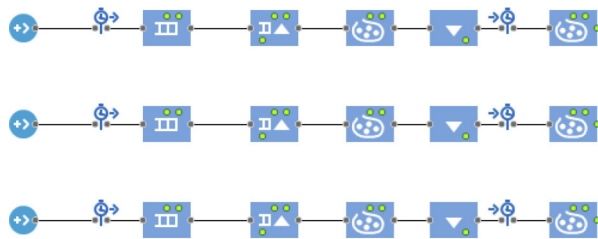


Fig. 4 Model of truck-alone transportation.

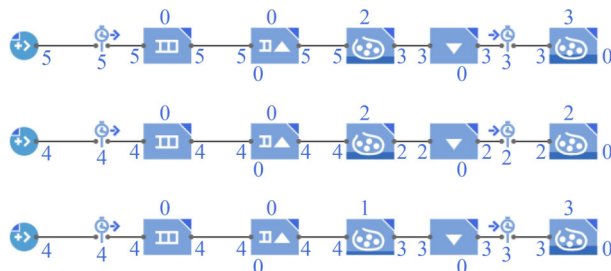


Fig. 5 Process of truck transportation.

performed with the above modules. The specific process modeling is illustrated in Fig. 4.

The model state during runtime is depicted in Fig. 5.

The remaining capacity of the resource pool indicates the availability of vehicles. As illustrated in Fig. 5, the simulation currently includes one energy supply truck, one first aid supply truck, and two survival supply trucks engaged in transportation tasks.

The detailed process modeling of joint transportation via trucks and aircraft is depicted in Fig. 6.

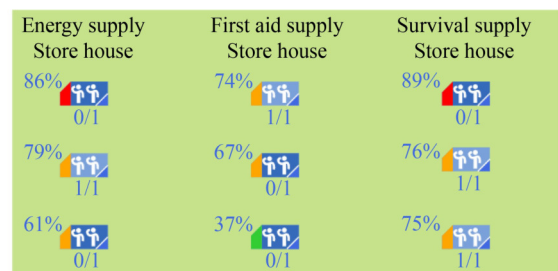
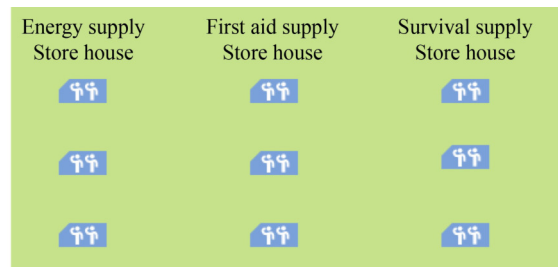
Given the sudden and unpredictable nature of emergencies, it is crucial to consider the possibility of recurring disasters in both the affected area and its surrounding regions. This section acknowledges the uncertainty inherent in emergencies and introduces risk areas to simulate the potential impact of disaster recurrence on emergency supply transportation.

We simulate four main scenarios: truck transportation, truck transportation in an uncertain environment, joint transportation, and joint transportation in an uncertain environment.

(1) **Scenario 1:** Truck transportation

The simulation results for 100 samples of truck transportation without considering adverse environmental factors are depicted in Fig. 7. Specifically, Fig. 7(a) shows the time distribution for energy supply transportation, Fig. 7(b) shows the time distribution for first aid supply, and Fig. 7(c) shows the time distribution for survival supply transportation. As shown in Fig. 7, the average transportation time for delivering 100 samples of energy, first aid, and survival supplies in this scenario is 121.36 h.

(2) **Scenario 2:** Truck transportation considering an uncertain environment



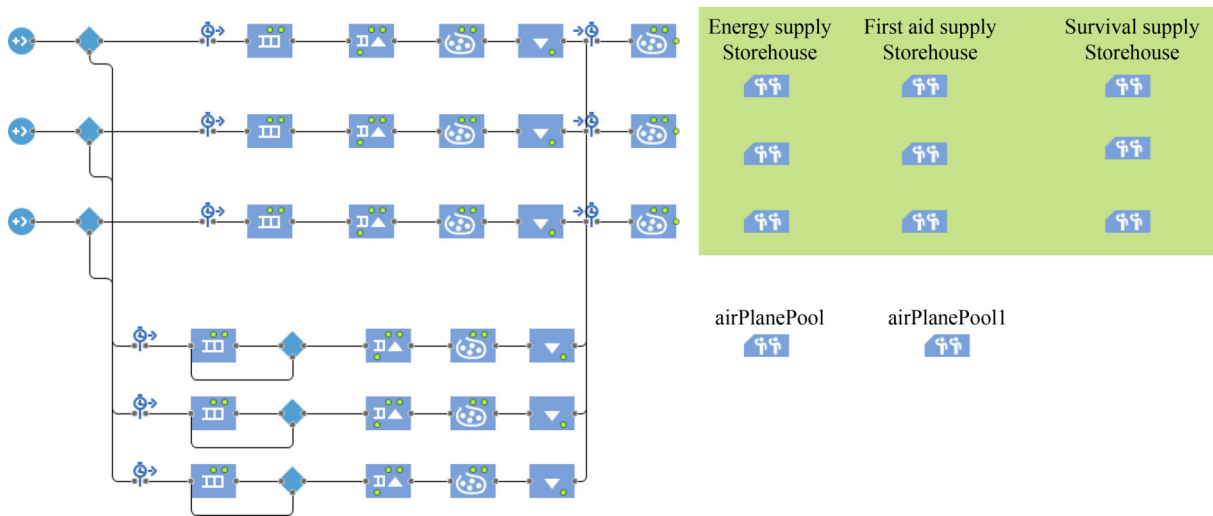


Fig. 6 Model of joint transportation.

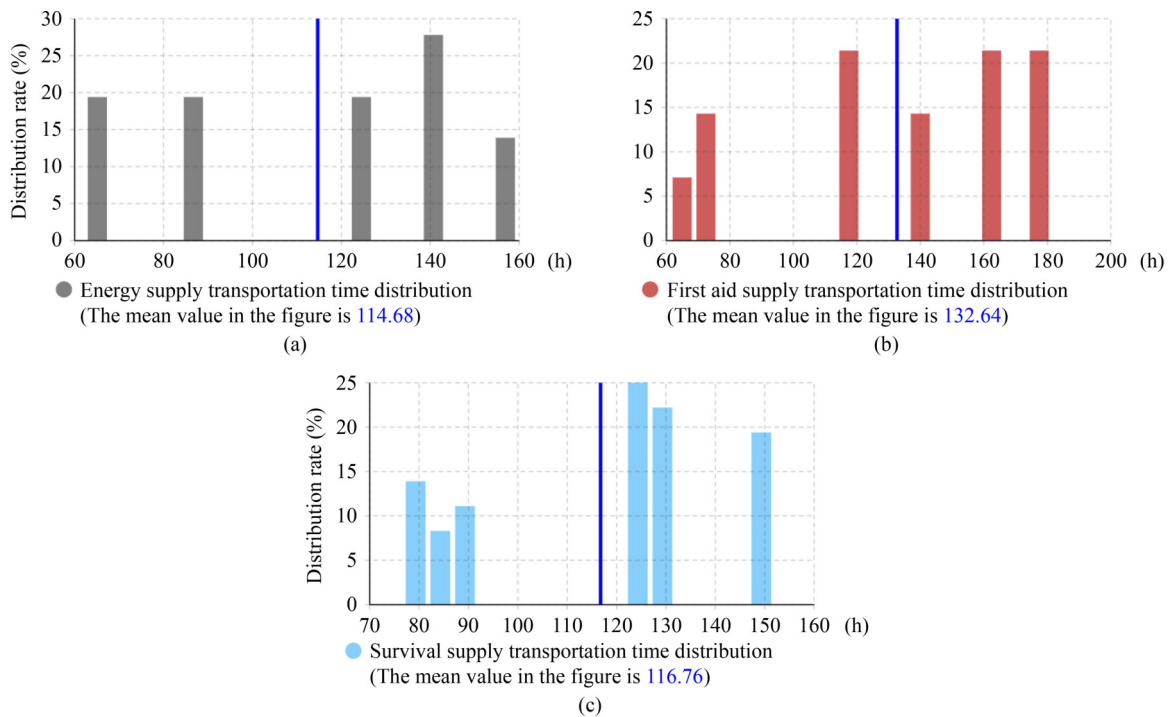


Fig. 7 Emergency supply transportation time distributions in Scenario 1: (a) Energy supply transportation time distribution; (b) First aid supply transportation time distribution; (c) Survival supply transportation time distribution.

Considering the effects of uncertain disasters, the simulation results for 100 samples are shown in Fig. 8.

The average transportation time for delivering 100 samples of energy, first aid, and survival supplies in this case is 154.59 h.

(3) Scenario 3: Joint transportation

When joint transportation is utilized without accounting for the impact of an uncertain environment, the simulation results for 100 transportation samples are depicted in Fig. 9.

In this case, the average transportation time for delivering

100 samples of energy, first aid, and survival supplies is 66.09 h.

(4) Scenario 4: Joint transportation in an uncertain environment

The simulation results for joint transportation based on truck transportation, with the addition of risk areas for 100 samples, are displayed in Fig. 10.

The average transportation time for delivering 100 samples of energy, first aid, and survival supplies in this case is 78.95 h.

The risks of the four scenarios are evaluated via the

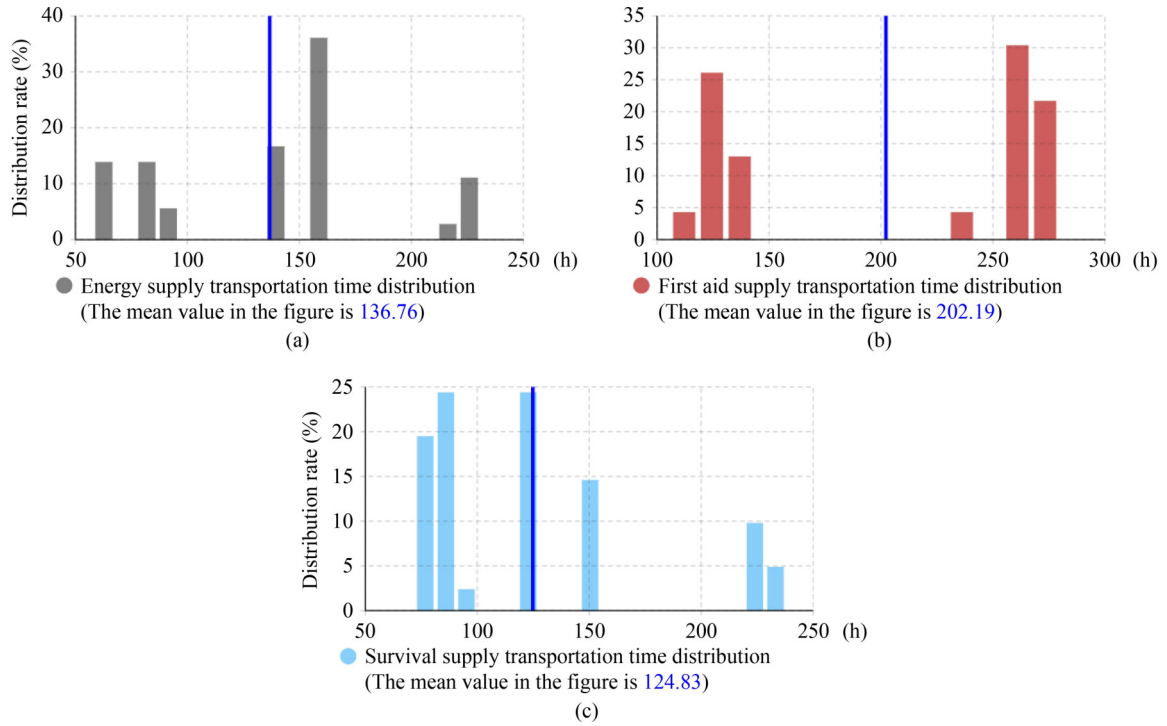


Fig. 8 Emergency supply transportation time distributions in Scenario 2: (a) Energy supply transportation time distribution; (b) First aid supply transportation time distribution; (c) Survival supply transportation time distribution.

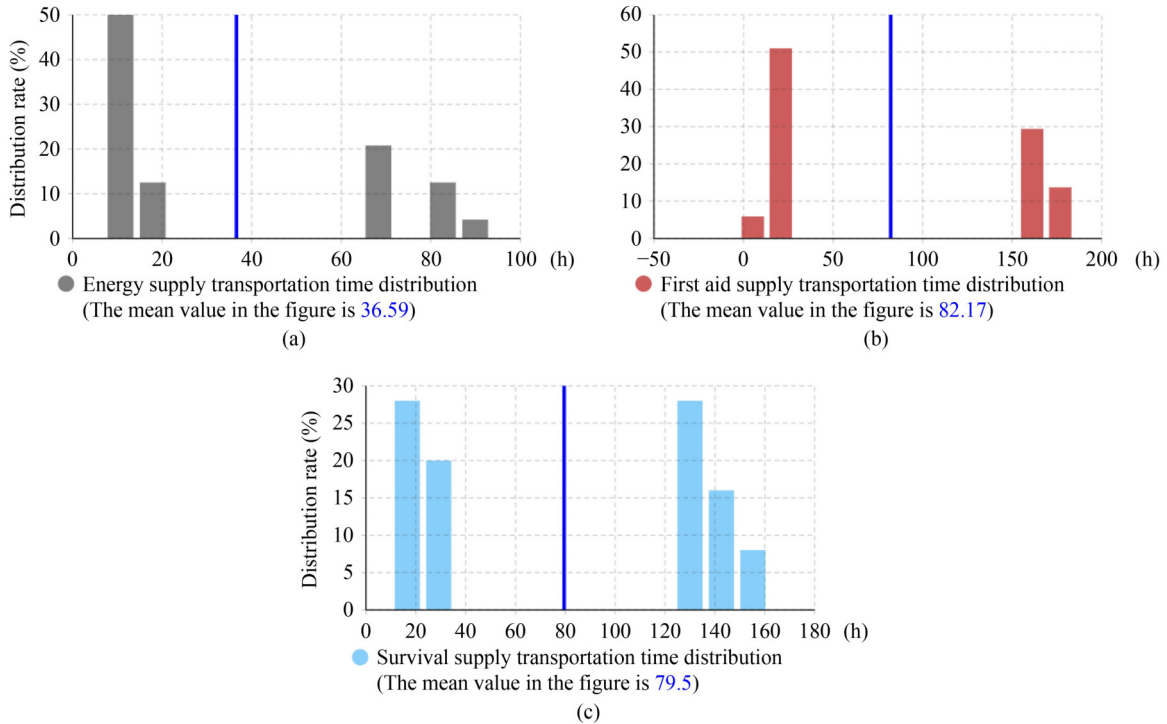


Fig. 9 Emergency supply transportation time distributions in Scenario 3: (a) Energy supply transportation time distribution; (b) First aid supply transportation time distribution; (c) Survival supply transportation time distribution.

risk assessment model proposed in Section 3.3, as shown in Table 5.

Table 5 shows that joint transportation surpasses truck

transportation in terms of cost. While truck transportation may offer simplicity and cost-effectiveness, joint transportation provides a significant time advantage.

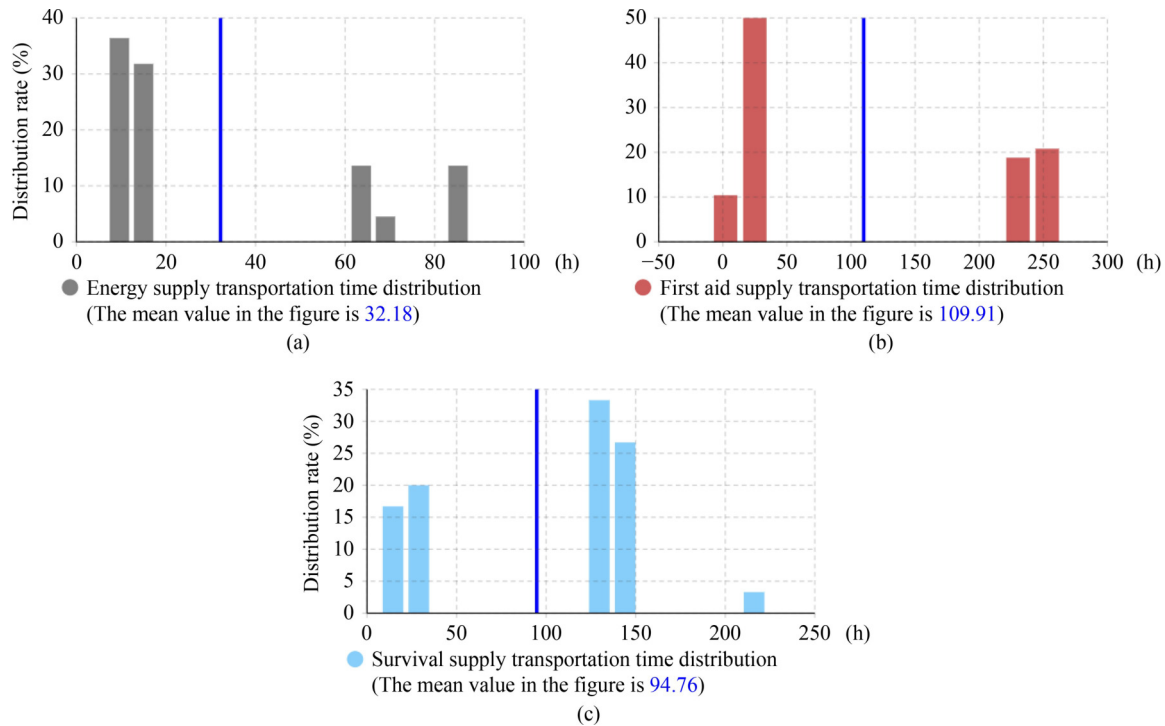


Fig. 10 Emergency supply transportation time distributions in Scenario 4: (a) Energy supply transportation time distribution; (b) First aid supply transportation time distribution; (c) Survival supply transportation time distribution.

Table 5 Comparison of simulation results

Indexes	Scenarios 1	Scenarios 2	Scenarios 3	Scenarios 4
Mean transportation time for supplies (h)	121.36	154.59	66.09	78.95
Total cost (yuan)	10726.32	11425.08	18318.08	19513.4
Total expected cost (yuan)	3217.896	5712.54	1911.116	2927.01

Compared with the use of trucks alone, joint transportation can reduce the transport time by at least half. This reduced transportation time for emergency supplies enhances the rescue efficiency, particularly during the rescue and recovery phases. Timely delivery of emergency supplies is crucial for minimizing the risks and hardships faced by victims and affected individuals. A comparison of scenarios 1 and 3, as well as scenarios 2 and 4, reveals that joint transportation effectively reduces transportation time and mitigates risks within the transportation system.

A comparison of scenarios 1 and 2, as well as scenarios 3 and 4, reveals that an uncertain environment contributes to an increase in both the average transportation time and the total expected cost. In the case of truck transportation, the average time increases from 121.36 h to 154.59 h. With the presence of risk areas, the transportation time for emergency supplies experiences a 27.38% increase. Similarly, for joint transportation, the average time increases from 66.09 h to 78.95 h, a 19.45% increase. These findings demonstrate that in the face of an uncertain environment, joint transportation effectively mitigates the impact of uncertainties on emergency supply transportation and reduces the risk of transportation system failure.

6 Conclusions and future work

The TCPS represents an intelligent integration of physical systems and information technology, playing a crucial role in the transportation of emergency supplies. It furnishes managers with real-time data and information for swift responses to emergencies. This study develops a risk assessment model based on the TCPS to evaluate transportation risk across different modes. The model accounts for transportation time costs, expenses, and delays while also considering the uncertainties that are inherent in disasters. By simulating the impact of emergency events, we assess the risk of emergency supply transportation across four scenarios, utilizing a Chinese city as a case study. The simulation outcomes demonstrate the model's efficacy in evaluating transportation risks and provide insights for decision-making in emergency supply transportation.

However, several limitations should be considered. This paper primarily quantifies the impact of disaster recurrence on emergency supply transportation in terms of cost. Future research should aim to quantify the effects

of disaster recurrence on transportation more comprehensively. Additionally, optimization algorithms for determining optimal transportation paths under uncertain conditions are limited. When an order cannot be transported by a truck, we consider changing the path under cost constraints or factoring in more transportation modes in the model. Future studies will prioritize addressing these aspects.

Competing Interests The authors declare that they have no competing interests.

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