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# Truck Scheduling Problem Considering Carbon Emissions under Truck Appointment System

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**Abstract:** Aiming at the truck scheduling problem between the outer yard and multi-terminals, the appointment optimization model of truck is established. In this model, the queue time and the operation time of truck during the appointment period of different terminals are different. Under the restriction of given appointment quotas of each appointment period, determine the arrival amount of trucks in each appointment period. The goal is to reduce carbon emissions and total costs, improve the efficiency of truck scheduling. To solve this model, hybrid genetic algorithm with variable neighborhood search was designed. Firstly, generate chromosomes, and the front part of the chromosome represents the demand for 40 ft containers and the back part represents the demand for 20 ft containers. Then, the route is generated according to the time constraint and appointment quotas of each appointment period. Finally, the neighborhood search strategy is adopted to improve the solution quality. The validity of the model and algorithm were verified by an example. A low-carbon scheduling scheme was obtained under truck appointment system. The results show that the scheduling scheme under truck appointment system uses fewer trucks, improves the efficiency of delivery, reduces the total costs, and it takes into account the requirements of low carbon.

**Keywords:** carbon emissions; truck appointment system; container terminal; multi-types containers; hybrid genetic algorithm with variable neighborhood search

## 1. Introduction

In recent years, the rapid growth of container throughput has put forward higher requirements on the efficiency and service capacity of container terminals. On the one hand, the amount and intensity of operation in the terminals have increased. On the other hand, many trucks arrive at the terminal in the peak period causing terminal gate congestion. Terminal gate congestion leads to longer queue time, which reduces truck turnover efficiency, thereby trucks perform fewer tasks in a day. It is important to note that the truck is idling during the queueing at the terminal gate, they will consume fuel, resulting in fuel costs. The way for micro and small enterprises to reduce total costs is correct to supply chain management [1], while the main cost structure of larger enterprises is fuel cost [2]. Reducing fuel costs can effectively reduce total costs of larger enterprises. If idling time is too long, trucks will emit a greater amount of emissions compared to when they are moving. As is known to all, these emissions from trucks increase the risk of heart disease, asthma attacks, strokes and untimely deaths [3], and massive carbon emissions contribute to global warming. In recent years, the hot issue of greenhouse gas emissions reduction has attracted close attention from all over the world [4].

At present, there are two approaches to alleviate terminal gate congestion, one approach is to increase infrastructures, such as the number of gates and the area of the terminal. Another approach is to manage truck arrival and adopt a truck appointment system (TAS). In the TAS, the terminal operator announces the opening time and the maximum number of containers that can be accepted (appointment quotas) in each appointment period through the network information system. The truck driver can choose the arrival time according to his preference. TAS is an effective approach to alleviate the terminal gate congestion. TAS was first proposed by the local government of California [5]. TAS saves a lot of time and reduces air pollution and alleviates terminal gate congestion by spreading the demands of terminals over different appointment periods of the day. Since 1999, in practical application, TAS has achieved successful experience in Vancouver port [6] and Tianjin port [7].

Truck scheduling has always been a key link in the process of container terminal operation. The terminal divides the day into multiple appointment periods and sets the appointment quotas for each appointment period. The appointment quotas are determined by the yard crane availability. They are also set to avoid potential conflicts with other operations in a certain yard block or zones, such as vessel operations, warehouse operations, rail operations, and customs inspections [8]. Some scholars have studied truck scheduling under TAS. Chen G, Chen X et al. [9,10] established the appointment optimization model of trucks with the goal of simultaneously minimizing the waiting time of trucks and adjusting the number of trucks in each appointment period before and after the appointment. However, most researches under TAS is that truck is scheduled between single outer yard and single terminal at present. Assuming that terminal only has the demand for one type of container. However, in reality, the outer yard has a strong service capacity and generally performs the delivery service for multiple terminals at the same time. Terminal has the demand for both 40 ft containers and 20 ft containers. Thus, an effective truck scheduling scheme under TAS must service not only a single terminal, but also multiple terminals, and trucks can deliver different types of containers.

Based on the above analysis, this paper studies the truck scheduling problem about a single outer yard serving multiple terminals from the perspective of carbon emissions and TAS. The mixed-integer programming formulation of truck scheduling is proposed. A hybrid genetic algorithm with a variable neighborhood search (HGAVNS) is designed. Finally, an example is given to show that the HGAVNS can effectively reduce the total costs of scheduling, thereby reduce the carbon emissions of trucks and achieve the goal of truck scheduling between a single outer yard and multiple terminals.

The remainder of the paper is organized as follows: Section 2 reviews the related literature. Section 3 presents a description of the problem and proposed a mixed-integer programming formulation. Section 4 gives the details of the hybrid genetic algorithm with a variable neighborhood search. Computational results on the example of a port in China are reported in Section 5. Conclusions and future research directions are suggested in Section 6.

## 2. Literature Review

As mentioned previously, a number of scholars have studied the truck scheduling under TAS. Huynh [5] took into account both the turnover time of trucks and the utilization rate of yard crane and calculated the appointment quotas of each appointment period with the method of planning model and simulation joint optimization. On this basis, Huynh et al. [11] also considered how to determine the upper limit of the number of containers that can be accommodated in each container area in each time window in the case of missing the appointment. Zhang et al. [12] constructed a second-level queueing network of gate and yard and established appointment optimization model of trucks in order to minimize the average turnover time of trucks. In order to further improve the flexibility of TAS, Chen G et al. [13] relaxed the assumption that the expected arrival mode of trucks is known and proposed a dynamic TAS. Torkjazi et al. [8] designed a TAS to minimize the impact on the terminal and the operation of trucks, which not only alleviated terminal gate congestion but also made the truck deviate from its original arrival time as little as possible. Zehendner et al. [14] proposed a mixed-integer linear programming model of appointment quotas and cross-truck scheduling optimization, which not only could improve the service quality of trucks, but also improve the service quality of trains and ships. Obviously, delivery under TAS effectively reduces the queue time of trucks in terminal gate and the turnover efficiency of truck is greatly improved. However, appointment periods and appointment quotas also add new constraints to the operation and management of truck company. Namboothiri et al. [15] constructed a truck scheduling optimization model of a single truck company considering the constraint of appointment periods to reduce the transportation costs of truck fleet. Islam and Olsen [16] emphasized that the reducing of the truck's flexibility and the possibility of sharing transportation capacity between truck companies were major challenges faced by the implementation of the TAS. Therefore, the operation strategy directly affected the benefits generated by the implementation of TAS. Schulte et al. [17] established a cooperative scheduling model of multiple trucks under the TAS, which reduced the travel distance of trucks when truck is empty, thus reduced the costs and carbon emissions. Phan et al. [18] studied the trucks' appointment optimization problem under the joint decision of terminal and truck company by establishing a mathematical model that included two subproblems, namely, prediction of truck turnover time and truck scheduling optimization plan. Chen et al. [19] proposed a "ship dependent time window" method to control the arrival of the truck and alleviate the terminal gate congestion. Traditional genetic algorithms, multi-social genetic algorithms, hybrid genetic algorithms, and simulated annealing algorithms were used to solve the problem. Niu et al. [20] studied a problem with truck scheduling and container area allocation. He proposed a particle swarm optimization algorithm and colony optimization algorithm based on swarm intelligence technology to solve the problem. Zhang et al. [21] proposed a new truck system optimization method to reduce the waiting time of trucks at the terminal gate and the operation time of trucks in the terminal, and estimated the waiting time of trucks with non-stationary queuing theory and verified the validity of the algorithm and model with numerical experiments. However, these studies are the truck scheduling between single outer yard and single terminal. Terminal only has a demand for one type of container. They haven't studied the problem of trucks service multiply terminals and each terminal has a demand for two types of containers under TAS.

For research on calculating carbon emissions has been addressed by Sim [22], he proposed a system dynamic method to evaluate the total carbon emissions of trucks in container terminals, including loading and unloading containers, container transportation, container terminal operation, and calculated the carbon emissions reduction of trucks from 2017 to 2030. Heilig et al. [23] put forward a multi-objective delivery problem considering carbon emissions, using the archive of simulated annealing method and a kind of visualization technology to solve. On this basis, Heilig et al. [24] deepen the earlier study by building a multi-objective model. The goal of this model is to minimize fixed costs, variable transportation costs, and carbon emissions. Yu et al. [25] proposed a method to evaluate the carbon emissions of trucks in the loading process. Li et al. [26] used the total waiting time and the carbon emissions when trucks are idling to balance the service quality and the green performance of the whole system. He et al. [27] proposed a mixed-integer programming model on the truck scheduling problem. The goal is to minimize all trucks delay deviation and the total transportation energy consumption of trucks. A synthetic optimization method based on simulation is proposed to solve the problem. The method is evaluated by simulation and spatial optimization algorithm. Wang et al. [28] predicted the $CO_2$ emissions using the Motor Vehicle Emission Simulator (MOVES). The results show that good road conditions can reduce $CO_2$ emissions. Tolliver et al. [29] used two methods to estimate fuel consumption both from weight and distances based on different truck types. It pointed out that different truck configurations have a great impact on fuel consumption and route selection.

At present, most of the researches on truck scheduling are focused on the inner trucks and few studies are focused on the outer trucks. Compared with the inner trucks, the outer trucks serve multiple terminals and have a longer transportation distance, so the truck scheduling scheme has a greater impact on the waiting time. As the number of outer trucks is also limited, its waiting time will decrease the overall turnover efficiency of trucks. In view of these problems, we study the problem of trucks delivering containers from outer yard to terminals. The truck appointment optimization model is established from the perspective of carbon emissions and TAS. The hybrid genetic algorithm with variable neighborhood search (HGAVNS) was designed based on the advantages of genetic algorithm (GA) and variable neighborhood search (VNS) to solve the model. The goal of this model is to minimize the total costs including fixed costs, opportunity loss costs, carbon emissions costs, and fuel costs.

## 3. Problem Description and Formulation

### 3.1. Problem Description

This paper considers truck scheduling between an outer yard and multiple terminals under TAS form the perspective of carbon emissions. There are a number of trucks can be used to deliver containers. Trucks must meet the demand of terminals within the time window.

Under the TAS, an effective link has been established between each terminal and the outer yard. The outer yard can predict (generally 24 h in advance) the demand of each terminal. The demand of each terminal is determined by the number of vessels need to load. The terminal divides the day into multiple appointment periods and gives the appointment quotas of each appointment period. The appointment quotas are different in different appointment periods of each terminal. The waiting time at the terminal gate and the operation time inside terminal are also different. The terminal needs to ensure a certain length of each appointment period so that trucks can reach the terminal during appointment period. The outer yard selects appropriate appointment periods according to its own transportation capacity and gives the plan of the number of different types of containers will be carried by trucks during this period. Terminals determine the final plan and notice outer yard. The outer yard arranges the transportation capacity according to the specific plan of each terminal. The number of containers transported to the terminal must meet the demand of each terminal. The scheduling scheme of this paper is to use limited truck resources to arrange a certain number of trucks delivering containers to different terminals in different appointment periods. A truck can carry one 40 ft container or two 20 ft containers at the same time. While meeting the limitation of appointment quotas in each appointment period and the demand of each terminal, the scheduling scheme should save energy consumption and improve the benefit and efficiency of the outer yard.

Figure 1 shows the operation flow of trucks from a single outer yard to multiple container terminals. Truck 1 and truck 3 both deliver containers going to one terminal respectively. Trucks enter the terminal gate and unload containers. After finishing the scheduling task, trucks return to the outer yard and wait until the next scheduling task. In reality, if the demand for 20 ft containers is odd, this can happen a truck delivers two 20 ft containers going to two terminals. For example, truck 2 delivers two 20 ft containers going to terminal 1 and terminal 2 respectively. Firstly, truck 2 arrives at terminal 1 and unloads the container. Then, truck 2 goes to terminal 2. If the arrival time is within the appointment period of terminal 2, truck 2 enter the terminal 2 and unload the container immediately. Otherwise, truck 2 need to wait outside the terminal 2 until the appointment period. After truck 2 unload the container, truck 2 return to the outer yard and wait until the next scheduling task. The trucks are idling during queuing at the terminal gate and operating inside terminal. At this point, truck has energy consumption. When truck waits outside the terminal, there will be opportunity loss costs.

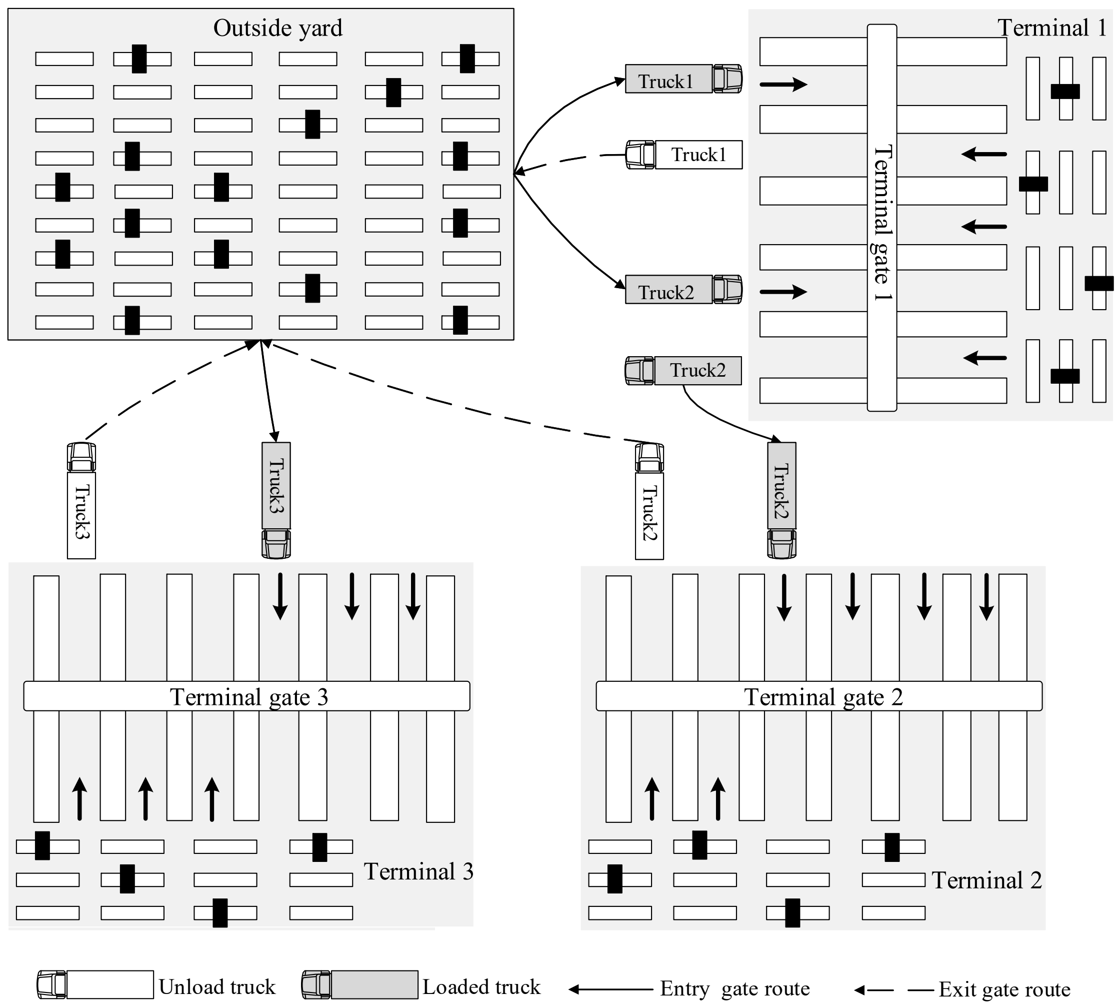


**Figure 1.** The operation flow of trucks from the single outside yard to multiple terminals.

## 3.2. Assumptions

This study is based on the following assumptions:

(1) Under the TAS, each terminal divides each day into 12 appointment periods (the length of each appointment period is 2 h). The period division of each terminal is consistent. If each appointment period is too long, the queue time of the truck at the terminal gate and the operation time inside the terminal are inaccurate. If each appointment period is too short, the queue time of the truck at the terminal gate and the operation time inside the terminal are accurate, but the flexibility of the truck scheduling is too poor. This paper assumes each appointment period is 2 h, which ensures the accuracy of queue time and operation time and the flexibility of the truck scheduling.

(2) Under the TAS, the truck starts timing from the moment 0. The loading time in the outer yard is mainly determined by the yard crane. This study assumes that it takes an average of 3 min loading a container. Unloading time and transportation time inside the terminal can be unified into the operation time inside the terminal. The operation time is related to the arrival time of the truck. The operation time of each terminal varies in different appointment periods. Transportation time between outer yard and terminal is directly related to the distance. The waiting time includes the waiting time at outer yard, waiting time outside the terminal and queue time at terminal gate. The waiting time at the outer yard is related to the truck scheduling scheme. The queue time at terminal gate varies in different appointment periods.

(3) A terminal has the demand for both 20 ft containers and 40 ft containers and the number is constant. Since non-standard containers are rarely used in reality and there are no trucks of the same size as the non-standard containers. This paper assumes that each terminal only has the demand for 20 ft containers and 40 ft containers.
(4) After unloading the container, the truck should return to the outer yard for the next scheduling. There is no energy consumption when the truck is waiting outside the terminal, but there are opportunity loss costs (in the comparison experiment, this can happen that truck is waiting outside the terminal). There are no costs when the truck is waiting at the outer yard for the next scheduling. There is energy consumption when the truck queues at the terminal gate, operates inside the terminal and loads containers at the outer yard.
(5) This paper assumes only has one type of truck. Driving speed, the coefficient values of $CO_2$ emissions and other performance of each truck are the same. All trucks use diesel and the coefficient values of $CO_2$ emissions are only related to the type of fuel.
(6) Trucks can make multiple trips between the outer yard and terminals to complete the scheduling task. A truck can carry one 40 ft container or two 20 ft containers.
(7) This paper doesn't consider other interference factors on the truck. Road conditions, weather, and other factors will affect the speed of the truck. This paper doesn't consider these factors and assumes the speed of the truck is fixed.
(8) Under the TAS, the terminal will allocate the time window and appointment quotas for the outer yard. Containers must be delivered to the terminal within the time window of it. If containers aren't delivered to the terminal within the time window of it, it will affect the vessel's delivery plan and cause great costs.

### *3.3. Parameters and Variables*

This paper sets the following variables:

(1) Input variables:

$I$: Set of container terminals,
0: Outer yard,
$K$: Set of trucks,
$P$: Set of appointment periods,
$L$: The length of each appointment period,
$Q_i^1$: The demand for 40 ft containers of terminal $i$,
$Q_i^2$: The demand for 20 ft containers of terminal $i$,
$\left[T_i^e, T_i^l\right]$: Delivery time window of terminal $i$,
$T_{pi}^e$: The time when the terminal $i$ starts to accept containers during the appointment period $p$,
$h_{pi}^1$: The appointment quotas of 40 ft containers during the appointment period $p$ of the terminal $i$,
$h_{pi}^2$: The appointment quotas of 20 ft containers during the appointment period $p$ of the terminal $i$,
$t_0$: Loading time of each container at the outer yard,
$N$: Set of the number of delivery times,
$d_{0i}$: Distance between the outer yard and terminal $i$,
$d_{ij}$: Distance between terminal $i$ and terminal $j$,
$v$: The speed of truck, unit: km/h,
$t_{pi}^g$: The queue time of truck at terminal gate $i$ during the appointment time $p$,
$t_{pi}^o$: The operation time of truck inside terminal $i$ during the appointment time $p$,
$c^k$: The fixed cost of each truck,
$c^w$: The unit opportunity loss costs of truck waits outside the terminal,

$e^o$: The coefficient values of $CO_2$ emissions: kg/L,
$c^r$: The cost tax of per unit of carbon emissions: Yuan/kg,
$c^o$: The cost of per unit of fuel: Yuan/L,

(2) Intermediate variables:

$Q^1_{i,k}$: The number of 40 ft container delivered by truck $k$ to the terminal $i$,
$Q^2_{i,k}$: The number of 20 ft container delivered by truck $k$ to the terminal $i$,
$Q^1_{pi,k}$: The number of 40 ft container delivered by truck $k$ to the terminal $i$ during the appointment period $p$,
$Q^2_{pi,k}$: The number of 20 ft container delivered by truck $k$ to the terminal $i$ during the appointment period $p$,
$T_{pin,k}$: The moment of truck $k$ arriving at terminal $i$ during the appointment period $p$, this is the $n$ $th$ delivery of truck $k$,
$T^d_{pn,k}$: The moment of truck $k$ departing outer yard during the appointment period $p$, this is the $n$ $th$ delivery of truck $k$,
$t^w_{in,k}$: The waiting time of truck $k$ outside the terminal $i$, this is the $n$ $th$ delivery of truck $k$,
$T^m_{in,k}$: The moment of truck $k$ departing terminal $i$, this is the $n$ $th$ delivery of truck $k$,
$T^r_{pn,k}$: The moment of truck $k$ returning to the outer yard during the appointment period $p$, this is the $n$ $th$ delivery of truck $k$,
$t^y_{pn,k}$: The waiting time of truck $k$ at the outer yard before departing outer yard during the appointment period $p$, this is the $n$ $th$ delivery of truck $k$,

(3) Decision variables:

$y_k$: if truck $k$ is used, $y_k = 1$, otherwise, $y_k = 0$,
$y_{i,k}$: if truck $k$ delivers containers to terminal $i$, $y_{i,k} = 1$, otherwise, $y_{i,k} = 0$,
$y_{in,k}$: if truck $k$ delivers containers to terminal $i$, this is the $n$ $th$ delivery of truck $k$, $y_{in,k} = 1$, otherwise, $y_{in,k} = 0$,
$y_{ij,k}$: if truck $k$ delivers containers form node $i$ to node $j$, $y_{ij,k} = 1$, otherwise, $y_{ij,k} = 0$,
$y_{pi,k}$: if truck $k$ delivers containers to terminal $i$ during the appointment period $p$, $y_{pi,k} = 1$, otherwise, $y_{pi,k} = 0$.

### *3.4. Mathematical Model*

#### 3.4.1. The Optimization Goal Setting

(1) The fixed costs of trucks

The fixed costs of trucks include the purchase costs of trucks, driver's salaries, maintenance costs and so on. The trucks that incur fixed costs mainly refer to those perform scheduling tasks, except idle trucks. Additionally, it is not related to the mileage and the number of terminals. The fixed costs $C_1$ can be expressed as:

$$C_1 = \sum_{k \in K} c^k y_k \tag{1}$$

(2) Opportunity loss costs of trucks waiting outside the terminal

The trucks wait outside the terminal without energy consumption but there are opportunity loss costs. The opportunity loss costs $C_2$ can be expressed as:

$$C_2 = \sum_{n \in N} \sum_{i \in I} \sum_{k \in K} c^w t^w_{in,k} y_{in,k} \tag{2}$$

(3) The carbon emissions costs and fuel costs

Trucks emit $CO_2$ when trucks are idling or moving. According to literature [30], the distance traveled per volume unit of fuel is closely related to the truck's load. Referring to the calculation of fuel consumption costs in literature [30], this paper assumes that the weight of a truck is $Q_0$ when the truck is empty. One 40 ft container is heavier as two 20 ft containers. The weight of each 20 ft container is same. The maximum weight that a truck can carry is $Q$. The fuel consumption per unit distance is $\beta_1$ when truck is empty. The fuel consumption per unit distance is $\beta_2$ when truck is at full load. The fuel consumption of per unit distance can be expressed as: $\beta(Q_x) = a(Q_0 + Q_x) + b$. $a$ and $b$ are the coefficients of unitary linear expressions. $Q_x$ is the weight that the truck carried in the truck transportation process. The fuel consumption per unit distance in the truck transportation process is $\beta(Q_x)$. The fuel consumption per unit distance can be expressed as $\beta_1 = aQ_0 + b$ when truck is empty. The fuel consumption per unit distance can be expressed as $\beta_2 = a(Q_0 + Q) + b$ when a truck is at full load. It follows that $a = \frac{\beta_2 - \beta_1}{Q}$ and $b = \beta_1 - \frac{\beta_2 - \beta_1}{Q} Q_0$. Then the fuel consumption of per unit distance in the truck transportation process can be expressed as:

$$\beta(Q_x) = a(Q_0 + Q_x) + b = \beta_1 + \frac{\beta_2 - \beta_1}{Q} Q_x \tag{3}$$

The calculation formula of $EM_1$ (the number of $CO_2$ emissions that trucks emit when trucks deliver containers form node $i$ to node $j$) can e expressed as:

$$EM_1 = e^o \sum_{i \in I \cup 0} \sum_{j \in I \cup 0} \sum_{k \in K} \beta(Q_{ij}) d_{ij} y_{ij,k} \tag{4}$$

The load of trucks in the transport process from node $i$ to node $j$ is $Q_{ij}$ and the distance from node $i$ to node $j$ is $d_{ij}$ and the fuel consumption of per unit distance in the truck transport process from node $i$ to node $j$ is $\beta(Q_{ij})$.

The truck is idling when truck loads containers and queues at the terminal gate and operates inside the terminal. Truck emits $CO_2$ when it is idling. The calculation formula of $EM_2$ (the number of $CO_2$ emissions that trucks emit when they are idling) can be expressed as:

$$EM_2 = e^o (\sum_{p \in P} \sum_{i \in I} \sum_{k \in K} (t^g_{pi} + t^o_{pi}) y_{pi,k} + \sum_{i \in I} \sum_{k \in K} t_0 (Q^1_{i,k} + Q^2_{i,k}) y_{i,k}) \tag{5}$$

This paper introduces carbon tax mechanism to calculate carbon emissions costs. If the carbon tax is $c^o$, the carbon emissions costs $C_3$ can be expressed as:

$$\begin{aligned} C_3 &= c^r (EM_1 + EM_2) \\ &= c^r e^o (\sum_{i \in I \cup 0} \sum_{j \in I \cup 0} \sum_{k \in K} \beta(Q_{ij}) d_{ij} y_{ij,k} + \sum_{p \in P} \sum_{i \in I} \sum_{k \in K} (t^g_{pi} + t^o_{pi}) y_{pi,k} + \sum_{i \in I} \sum_{k \in K} t_0 (Q^1_{i,k} + Q^2_{i,k}) y_{i,k}) \end{aligned} \tag{6}$$

The fuel costs $C_4$ can be an expression as:

$$C_4 = (EM_1 + EM_2) / e^o * c^o \tag{7}$$

### 3.4.2. Optimize Model Settings

In Section 3.4.1, fixed costs, opportunity loss costs, carbon emissions costs, and fuel costs are comprehensively considered. The corresponding optimization model is given by the following:

$$\begin{aligned}\min C = & \sum_{k\in K} c^k y_k + \sum_{n\in N}\sum_{i\in I}\sum_{k\in K} c^w t^w_{in,k} y_{in,k} \\ & +(c^r e^o + c^o)\Big(\sum_{i\in I\cup 0}\sum_{j\in I\cup 0}\sum_{k\in K}\beta(Q_{ij}) d_{ij} y_{ij,k} \\ & +\sum_{p\in P}\sum_{i\in I}\sum_{k\in K}(t^g_{pi}+t^o_{pi}) y_{pi,k} + \sum_{i\in I}\sum_{k\in K} t_0 (Q^1_{i,k}+Q^2_{i,k}) y_{i,k}\Big)\end{aligned} \tag{8}$$

$$\sum_{k\in K} Q^1_{i,k} y_{i,k} = Q^1_i, \forall i\in I \tag{9}$$

$$\sum_{k\in K} Q^2_{i,k} y_{i,k} = Q^2_i, \forall i\in I \tag{10}$$

$$\sum_{p\in P} Q^1_{pi,k} y_{pi,k} = Q^1_{i,k}, \forall i\in I, \forall k\in K \tag{11}$$

$$\sum_{p\in P} Q^2_{pi,k} y_{pi,k} = Q^2_{i,k}, \forall i\in I, \forall k\in K \tag{12}$$

$$\sum_{i\in I} y_{i,k} = y_k \forall k\in K \tag{13}$$

$$\sum_{n\in N} y_{in,k} = y_{i,k} \forall i\in I, \forall k\in K \tag{14}$$

$$\sum_{p\in P} y_{pi,k} = y_{i,k} \forall i\in I, \forall k\in K \tag{15}$$

$$\sum_{k\in K} Q^1_{pi,k} y_{pi,k} \le h^1_{pi}, \forall p\in P, \forall i\in I \tag{16}$$

$$\sum_{k\in K} Q^2_{pi,k} y_{pi,k} \le h^2_{pi}, \forall p\in P, \forall i\in I \tag{17}$$

$$T^d_{p1,k} = T^r_{(p-1)n,k} + t^y_{p1,k} + t_0, \forall p\in P, \forall k\in K, \forall n\in N \tag{18}$$

$$T^d_{p1,k} = T^r_{(p-1)n,k} + t^y_{p1,k} + 2t_0, \forall p\in P, \forall k\in K, \forall n\in N \tag{19}$$

$$T^d_{pn,k} = T^r_{p(n-1),k} + t^y_{pn,k} + t_0, \forall p\in P, \forall k\in K, \forall n\in N \tag{20}$$

$$T^d_{pn,k} = T^r_{p(n-1),k} + t^y_{pn,k} + 2t_0, \forall p\in P, \forall k\in K, \forall n\in N \tag{21}$$

$$T_{pin,k} = T^d_{pn,k} + d_{0i}/v, \forall p\in P, \forall i\in I, \forall k\in K, \forall n\in N \tag{22}$$

$$T^m_{in,k} = T_{pin,k} + t^g_{pi} + t^o_{pi}, \forall p\in P, \forall i\in I, \forall k\in K, \forall n\in N \tag{23}$$

$$T^r_{pn,k} = T^m_{in,k} + d_{0i}/v, \forall p\in P, \forall i\in I, \forall k\in K, \forall n\in N \tag{24}$$

$$T_{pjn,k} = T^m_{in,k} + d_{ij}/v, \forall p\in P, \forall i,j\in I, \forall k\in K, \forall n\in N \tag{25}$$

$$t^w_{jn,k} = \begin{cases} T^e_{pj} - T_{pjn,k}, T^e_{pj} > T_{pjn,k} \\ 0, T^e_{pj} \le T_{pjn,k} \end{cases}, \forall p\in P, \forall j\in I, \forall k\in K, \forall n\in N \tag{26}$$

$$T^m_{jn,k} = T_{pjn,k} + t^w_{jn,k} + t^g_{pj} + t^o_{pj}, \forall p\in P, \forall j\in I, \forall k\in K, \forall n\in N \tag{27}$$

$$T_{pi1,k} \ge T^e_i, \forall p\in P, \forall i\in I, \forall k\in K \tag{28}$$

$$T_{pin,k} \le T_i^l, \forall p \in P, \forall i \in I, \forall k \in K, \forall n \in N \tag{29}$$

$$y_k \in \{0,1\}, \forall k \in K \tag{30}$$

$$y_{i,k} \in \{0,1\}, \forall i \in I, \forall k \in K \tag{31}$$

$$y_{in,k} \in \{0,1\}, \forall i \in I, \forall k \in K, \forall n \in N \tag{32}$$

$$y_{ij,k} \in \{0,1\}, \forall i, j \in I \cup 0, \forall k \in K \tag{33}$$

$$y_{pi,k} \in \{0,1\}, \forall p \in P, \forall i \in I, \forall k \in K \tag{34}$$

The objective of our problem is to minimize the total costs in objective function (8). The total costs include fixed costs, opportunity loss costs, carbon emissions costs, and fuel costs. Constraints (9)–(15) represent the relationship between variables. Constraints (16) and (17) indicate that the number of containers delivered to the terminal $i$ by all trucks during the appointment period $p$ should less the appointment quotas of the appointment period $p$ of terminal $i$. Constraints (18) and (19) indicate the moment when truck $k$ departures the outer yard during the appointment period $p$, it is the first delivery of truck $k$. $T^r_{(p-1)n,k}$ indicates the moment when truck returns to the outer yard during the appointment period $p-1$, it is the $n$ $th$ delivery of truck $k$. $t^y_{p1,k}$ indicates the time that truck $k$ waits at the outer yard before it departures the outer yard during the appointment period $p$, it is the first delivery of truck $k$. The difference between constraint (18) and (19) is that constraint (18) indicates that truck $k$ only loads one container, and constraint (19) indicates that truck $k$ loads two containers. Constraints (20) and (21) indicate the moment when truck $k$ departures the outer yard during the appointment period $p$, it is the $n$ $th$ delivery of truck $k$. $T^r_{p(n-1),k}$ indicates the moment when truck $k$ returns to the outer yard during the appointment period $p$, it is the $n-1$ $th$ delivery of truck $k$. The difference between constraint (20) and (21) is that constraint (20) indicates that truck $k$ only loads one container, and constraint (21) indicates that truck $k$ loads two containers. Constraints (22) indicates the moment when truck $k$ arrives at the terminal $i$ during the appointment period $p$, it is the $n$ $th$ delivery of truck $k$. Constraints (23) indicates the moment when truck $k$ departures the terminal $i$, it is the $n$ $th$ delivery of truck $k$. Constraints (24) indicates the moment that truck $k$ returns to the outer yard form terminal $i$ during the appointment period $p$, it is the $n$ $th$ delivery of truck $k$. Constraints (25) indicate the moment that truck $k$ arrives at the terminal $j$ from terminal $i$ during the appointment period $p$, it is the $n$ $th$ delivery of truck $k$. Constraints (26) indicates the waiting time of truck $k$ outside the terminal $j$, it is the $n$ $th$ delivery of truck $k$. If the moment of truck $k$ arrived at terminal $j$ earlier than the moment of terminal $j$ begins to accept containers during the appointment period $p$, the waiting time $t^w_{jn,k} = T^e_{pj} - T_{pjn,k}$, otherwise, $t^w_{jn,k} = 0$. Constraints (27) indicate the moment that the truck $k$ departures terminal $j$, it is the $n$ $th$ delivery of truck $k$. Constraints (28) and (29) indicate the moment when truck $k$ arrives at terminal $i$ must within the time window of the terminal $i$. Constraints (30)–(34) define the domain of the variables.

## 4. Hybrid Genetic Algorithm with Variable Neighborhood Search

Genetic algorithm (GA), also known as evolutionary algorithm, was first implemented in the year 1984 [31]. The GA is a kind of highly parallel and strongly robust global search algorithm based on the principles of biological evolution in nature. It has disadvantages such as prematurity and slow convergence speed. Variable neighborhood search (VNS) contains a variety of neighborhood structures, which can effectively combine with other heuristic algorithms to conduct targeted local search. In this paper, the hybrid genetic algorithm with a variable neighborhood search (HGAVNS) was designed based on the advantages of GA and VNS. The algorithm flow is shown in Figure 2.

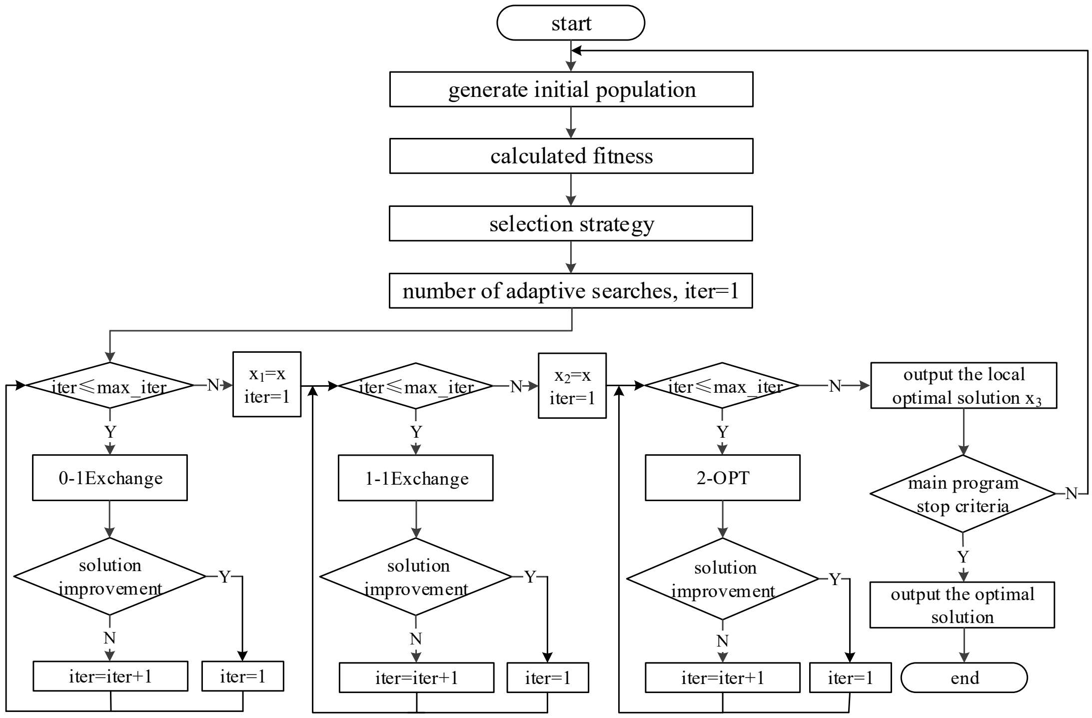


**Figure 2.** The basic flow of HGAVNS.

### *4.1. Coding and Generation Initial Population*

This paper studies the scheduling problem of trucks between the outer yard and multi-terminals. Since a truck only carries one type of container at the same time, so divides the chromosome into two parts. Each position on the chromosome represents a gene. The number of genes in the front part of the chromosome is determined by the demand for 40 ft containers of all terminals and the figure in each gene represents the terminal has the demand for a 40 ft container. The number of genes in the back part of the chromosome is determined by the demand for 20 ft containers of all terminals and the figure in each gene represents the terminal has the demand for a 20 ft container. The length of the chromosome is determined by the delivery number of all terminals.

Assume that terminal 1 needs three 40 ft containers and five 20 ft containers. Terminal 2 needs five 40 ft containers and two 20 ft containers. Terminal 3 needs seven 40 ft containers and five 20 ft containers. The specific coding method is shown in Figure 3.

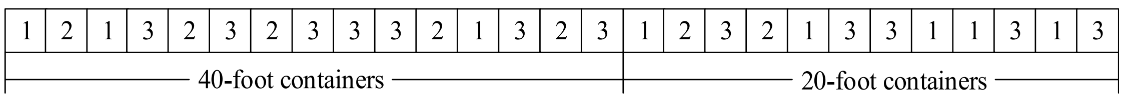


**Figure 3.** Coding mode diagram.

### *4.2. Fitness Function*

The fitness function of chromosomes can be expressed as:

$$f_R = \frac{1}{C_R} \tag{35}$$

$C_R$ is the objective function value of chromosome $R$, $f_R$ is the fitness function value of the chromosome $R$.

### 4.3. Selection Strategy

The individuals are arranged according to the fitness value. The individual with the highest fitness was marked 0. The individual with the lowest fitness was marked $pop\_size - 1$. It generates a random number $\varepsilon$ following a normal distribution. It has a 99.9% possibility of greater than -3 and smaller than 3. If $\varepsilon$ is greater than 3, a new random number $\varepsilon$ is generated once again. Make $\varepsilon^* = \left|\frac{\varepsilon}{3}\right|$, $\xi = \varepsilon^*(pop\_size - 1)$. Select $\xi$ individual to enter the new population for the next iteration.

### 4.4. Variable Neighborhood Search Strategy

In the traditional genetic algorithm, individuals are disturbed by crossover and mutation operations. The algorithm's ability to search the solution depth is insufficient and the computational efficiency is low. This paper introduces variable neighborhood search algorithm to conduct depth search on each individual and design adaptive evolutionary pressure, adaptive neighborhood search range and adaptive neighborhood search times (see Section 4.5 for setting method). It can reduce the neighborhood search scope and improve search efficiency and balance the breadth and depth of search. The pseudo-code of the variable neighborhood search algorithm is given below:

**Algorithm 1: Variable Neighborhood Search Algorithm**

Begin
1: set the neighborhood structure $N_k = \{N_1, N_2, \ldots, N_l\}$, $N_l$ is the *l th* neighborhood structure,
2: loop *max_N* times,
  2.1: Individual $R$ disturbed from the first neighborhood structure $N_1$, $iter \leftarrow 1$,
  2.2: if $f(R') \geq f(R)$
    {
      $R \leftarrow R'$,
      $iter \leftarrow 1$,
    },
  2.3: else
    {
      $iter \leftarrow iter + 1$
    },
  2.4 until ($iter = max\_iter$),
  2.5 Individual $R$ continues to be disturbed by the next neighborhood structure $N_l$, $iter \leftarrow 1$,
  2.6 repeat,
  2.7 until ($iter = max\_iter$),
  2.8 until (the optimal solution hasn't update when individuals were disturbed by the last neighborhood structure or neighborhood search has loop *max_N* times),
End.

The three neighborhood structures adopted in this paper are respectively 0-1Exchange, 1-1Exchange and 2-OPT. The diagram of a variable neighborhood search strategy is shown in Figure 4.

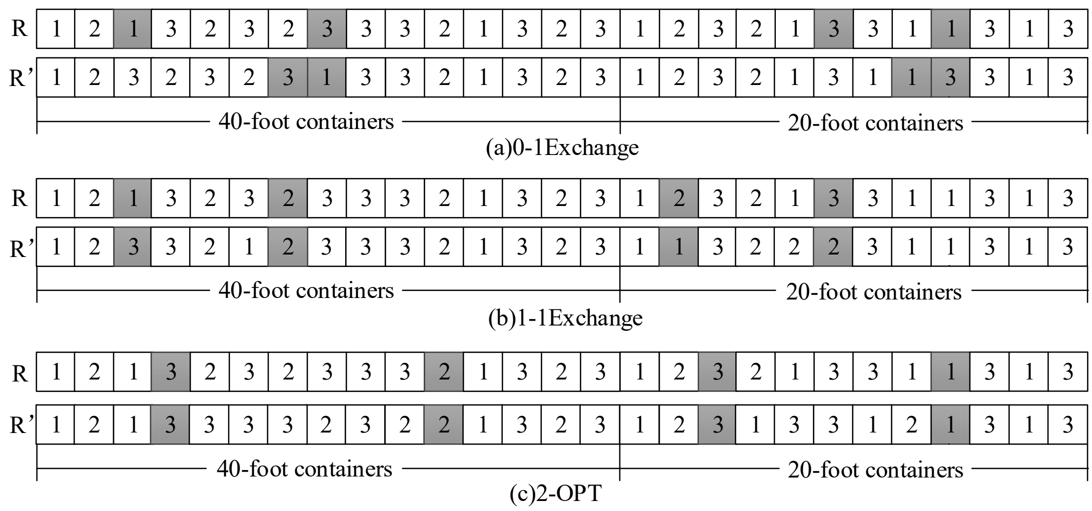


**Figure 4.** Diagram of a variable neighborhood search strategy.

### *4.5. Adaptive Search Strategy*

Due to the different pressures required in different stages of population evolution, adaptive evolutionary pressures, adaptive neighborhood search times strategy and adaptive neighborhood search range strategy are introduced in this paper to balance the breadth and depth by changing the population search range and neighborhood search times. The adaptive search strategies in this paper are as follows:

(1) Adaptive evolutionary pressure

The adaptive evolutionary pressure in this paper is as follows:

$$\lambda = \partial \cdot \exp\left(\frac{gen - max\_gen}{max\_gen}\right), \partial \in (0,1) \tag{36}$$

$\lambda$ is the evolutionary pressure, $\partial$ is the coefficient set to prevent the evolutionary pressure at the later stage of evolution from being 1(stop the evolution) and *max_gen* is the preset maximum number of iterations. *gen* indicates algorithm has been iterated *gen* times. This paper set $\partial = 0.8$.

(2) Adaptive neighborhood search times strategy

The adaptive search times strategy in this paper is as follows:

$$S_t = \alpha_1 + \left\lfloor \alpha_2 \left(\frac{gen}{max\_gen}\right)^{\frac{1}{2}} \right\rfloor \tag{37}$$

$S_t$ is the neighborhood search time. $\alpha_1$ represents the minimum search times and $\alpha_2$ is the adaptive search times. *max_gen* is the preset maximum number of iterations. *gen* indicates algorithm has been iterated *gen* times. $\lfloor\rfloor$ represents round down. It can be seen from the equation (37) that in the initial stage of evolution, the population has a low number of search times $\alpha_1$. With the continuous iteration of the population, the search times gradually increase. The maximum search times is $\alpha_1 + \alpha_2$. On the basis of maintaining the diversity of the population, the depth of exploration should be increased.

(3) Adaptive neighborhood search range strategy

The adaptive search range strategy in this paper is as follows:

$$S_r = \varpi_1(Q^1 + Q^2) + \left\lfloor \varpi_2(Q^1 + Q^2)\left(\frac{gen}{\max gen}\right)^{\frac{1}{2}} \right\rfloor \tag{38}$$

$S_r$ is the neighborhood search range. *max_gen* is the preset maximum number of iterations. *gen* indicates algorithm has been iterated *gen* times. $\lfloor\rfloor$ represents round down. $Q^1$ is the demand for 40 ft containers of all terminals. $Q^2$ is the demand for 20 ft containers of all terminals. In the initial stage of evolution, the minimum neighborhood search range is $\varpi_1(Q^1+Q^2)$. With the continuous iteration of the population, the neighborhood search range increases and the maximum search range is $(\varpi_1+\varpi_2)(Q^1+Q^2)$. Obviously, with the increase in the number of iterations, the search scope gradually expands from $\varpi_1(Q^1+Q^2)$ to $(\varpi_1+\varpi_2)(Q^1+Q^2)$. In order to increase the diversity of the population and make it difficult for the population to fall into the local optimum, the poor solution is accepted with a certain bad solution acceptance criterion.

### *4.6. Iteration Stop Criteria*

In the population iteration process, if it hasn't updated the optimal solution $\gamma \cdot max\_gen$ times or the number of iterations has reached the preset maximum iteration number, the iteration will be stopped. This paper set $\gamma = 0.1$.

### *4.7. Time Complexity Analysis*

For the HGAVNS, assuming the demand for 40 ft containers of all terminals is $Q^1$, the demand for 20 ft containers of all terminals is $Q^2$, the population size is *pop_size*, the maximum number of iterations is *max_gen*, the number of neighborhood searches is $S_n$, the number of neighborhood cycles is *max_N*. According to the algorithm flow in Figure 2, calculate the complexity $O(T_i)$ of each link $i$.

(1) Generate initial population: $O(T_1) = O\big(pop\_size \cdot (Q^1+Q^2)\big)$,
(2) Calculate the fitness value: $O(T_2) = O\big(max\_gen \cdot pop\_size \cdot (Q^1+Q^2)\big)$
(3) Select operation: $O(T_3) = O(pop\_size \cdot max\_gen)$,
(4) Variable neighborhood search strategy: $O(T_4) = O\big(3max\_gen \cdot pop\_size \cdot max\_N \cdot S_n \cdot (Q^1+Q^2)\big)$.
In conclusion, the total time complexity of the algorithm can be estimated as:

$$\begin{aligned} O(T) &= O(pop\_size \cdot (Q^1+Q^2) + max\_gen \cdot pop\_size \cdot (Q^1+Q^2)) \\ &+ pop\_size \ \cdot max\_gen + 3max\_gen \cdot pop\_size \cdot max\_N \cdot S_n \cdot (Q^1+Q^2)). \\ &= O(pop\_size \cdot max\_gen \cdot max\_N \cdot S_n \cdot (Q^1+Q^2)) \end{aligned}$$

## 5. Experimental Design and Results

### *5.1. Description of Experimental Problems*

A port in China is selected to study the truck scheduling problem. One outer yard has 100 trucks, each of which can carry one 40 ft container or two 20 ft containers. Seven terminals adjacent outer yard have established TAS, all of which have the demand for 20 ft containers and 40 ft containers. Each terminal divides a day into 12 appointment periods. The length of each appointment period is 2 h. The average driving speed of each truck is 60 km/h. The fuel consumption per unit distance is 0.8 L when the truck is empty. The fuel consumption per unit distance is 1.2 L when truck is at full load. Fuel consumption is 2.5 L/h when truck is idling. The $CO_2$ emissions coefficient is 2.65 kg/L. The carbon tax is 0.04 Yuan/kg. The fuel cost is 6.41 Yuan/L. The unit cost of the truck waiting outside the terminal is 40 Yuan/h. The fixed cost of each truck is 300 Yuan. The average loading time of a container at the outer yard is 3 min. The distance between the outer yard and each terminal is shown in Table 1. The delivery information of each terminal is shown in Table 2. The appointment quotas in different appointment periods of each terminal are shown in Table 3. The average waiting time of truck at the terminal gate and the average operation time inside each terminal are different in different appointment periods of each terminal. In this paper, time interval is divided by 1 h and the changing trend is shown in Figures 5 and 6. For ease of calculation, the unit of time is expressed in minutes.

**Table 1.** The distance between the outer yard and terminals.

| *No.* | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 20 | 40 | 30 | 25 | 40 | 25 | 35 |
| 1 | 20 | 0 | 25 | 15 | 10 | 25 | 15 | 15 |
| 2 | 40 | 25 | 0 | 15 | 15 | 20 | 10 | 15 |
| 3 | 30 | 15 | 15 | 0 | 25 | 10 | 15 | 10 |
| 4 | 25 | 10 | 15 | 25 | 0 | 15 | 25 | 10 |
| 5 | 40 | 25 | 20 | 10 | 15 | 0 | 15 | 20 |
| 6 | 25 | 15 | 10 | 15 | 25 | 15 | 0 | 25 |
| 7 | 35 | 15 | 15 | 10 | 10 | 20 | 25 | 0 |

**Table 2.** Delivery information of each terminal.

| *Indicators* / *No.* | $Q_i^1$/box | $Q_i^2$/box | $T_i^e$/min | $T_i^l$/min |
|---|---|---|---|---|
| 1 | 8 | 13 | 0 | 720 |
| 2 | 15 | 15 | 0 | 480 |
| 3 | 10 | 13 | 120 | 720 |
| 4 | 12 | 30 | 360 | 1080 |
| 5 | 19 | 10 | 240 | 960 |
| 6 | 20 | 10 | 600 | 1200 |
| 7 | 16 | 9 | 480 | 1320 |

**Table 3.** The appointment quotas during each appointment period of each terminal (unit: box).

| *No.* / *p* | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 0–120 | 1(2) | 6(8) | 0 | 0 | 0 | 0 | 0 |
| 120–240 | 6(10) | 9(8) | 1(2) | 0 | 0 | 0 | 0 |
| 240–360 | 2(8) | 2(4) | 9(9) | 0 | 1(4) | 0 | 0 |
| 360–480 | 1(1) | 1(2) | 5(4) | 1(2) | 12(4) | 0 | 0 |
| 480–600 | 1(1) | 0 | 1(2) | 5(8) | 7(2) | 0 | 1(2) |
| 600–720 | 2(1) | 0 | 1(2) | 3(6) | 1(1) | 1(6) | 9(6) |
| 720–840 | | 0 | 0 | 3(12) | 3(6) | 8(6) | 3(1) |
| 840–960 | 0 | 0 | 0 | 1(8) | 3(1) | 6(2) | 4(2) |
| 960–1080 | 0 | 0 | 0 | 5(10) | 0 | 6(2) | 2(1) |
| 1080–1200 | 0 | 0 | 0 | 0 | 0 | 1(1) | 4(2) |
| 1200–1320 | 0 | 0 | 0 | 0 | 0 | 0 | 1(1) |
| 1320–1440 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Note: The figures in brackets of Table 3 are the appointment quotas of 20 ft containers in each appointment period of each terminal.

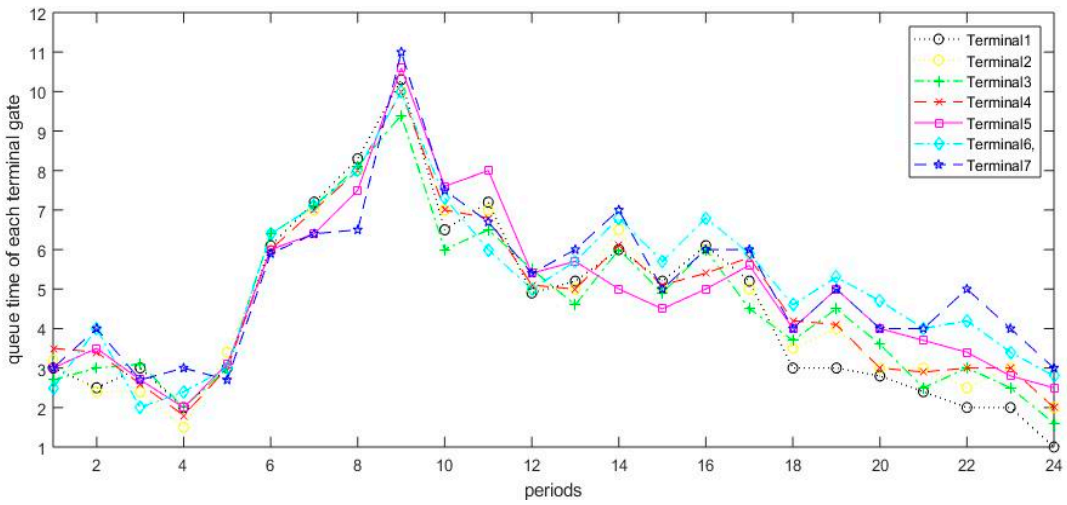


**Figure 5.** The queue time of each terminal gate in different appointment periods.

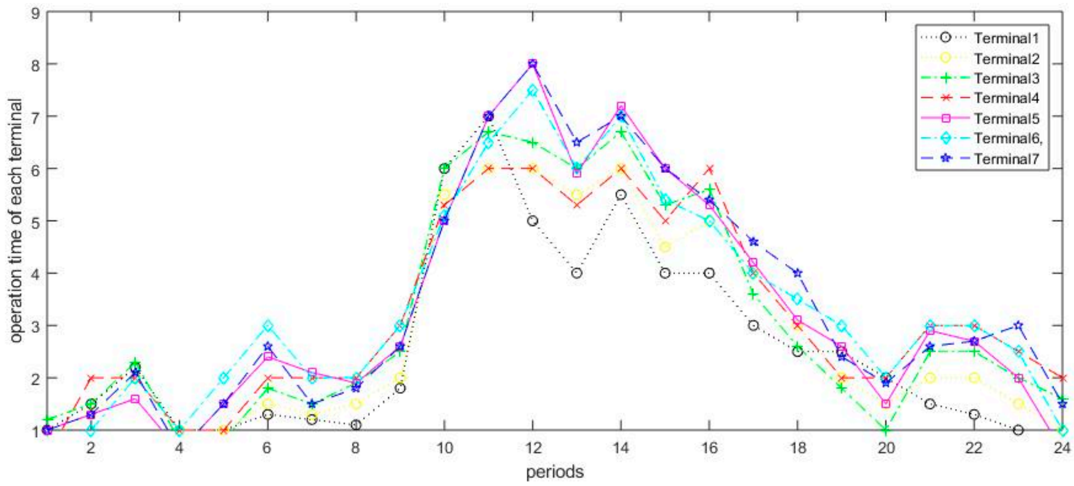


**Figure 6.** The operating time of each terminal in different appointment periods.

## 5.2. Parameter Setting and Results Analysis

This paper uses MATLAB R2018b to implement the proposed algorithm and model, and all experiments in this paper are evaluated on PCs with Intel(R) Core (TM) i7-7700 CPU @3.60 GHz and the memory of 16.0 GB. The parameters setting of the algorithm is shown in Table 4.

**Table 4.** Objective-related parameters.

| *Parameters* | *Value* |
|---|---|
| *pop_size* | 700 |
| max_*gen* | 800 |
| $\gamma$ | 0.1 |
| $\partial$ | 0.8 |
| $\alpha_1$ | 10 |
| $\alpha_2$ | 80~160 |
| $\varpi_1$ | 0.5~0.9 |
| $\varpi_2$ | 0~0.5 |

The model is solved by HGAVNS, and the optimal solution is 66642.83. In the optimal scheme, the scheduling sequence is shown in Appendix A Table A1. In Table A1, the order 1–14 in the first row represents the delivery order of relevant truck. This paper assumes $a$ represents the appointment period of the truck for this delivery. $b$ represents the number of containers loaded by the truck when departures from the outer yard. $c$ represents the serial number of the terminal. $d$ represents the time that returns to the outer yard after the previous delivery. $e$ represents the waiting time before this delivery at the outer yard. The first nine trucks deliver 40 ft containers. The delivery and operation conditions of these trucks are marked by $1 \times 4$ array. The $1 \times 4$ array's form is $(a, c, d, e)$. The last five trucks deliver 20 ft containers. The delivery and operation conditions of these trucks are marked by a $1 \times 5$ array. The $1 \times 5$ array's form is $(a, b, c, d, e)$.

The data in Table 5 presents the transportation mileage, working time, carbon emissions and the returning time in the last delivery of each truck under TAS. $d$ represents the transportation mileage of each truck. $T_l$ represents the total loading time of each truck. $T_w$ represents the total waiting time at outer yard of each truck. $T_q$ represents the total queue time at terminal gate of each truck. $T_o$ represents the total operation time at terminal of each truck, including unloading time and transportation time at terminal. $EM$ represents the number of carbon emissions of each truck. $T_r$ represents the returning time in the last delivery of each truck. $C$ represents the total costs.

**Table 5.** Operation information of optimal scheduling scheme under TAS.

| *No.* | $d$/km | $T_l$/min | $T_w$/min | $T_q$/min | $T_o$/min | $EM$/kg | $T_r$/min |
|---|---|---|---|---|---|---|---|
| 1 | 650 | 30 | 328.8 | 35.3 | 35.1 | 1733.67 | 1086.2 |
| 2 | 610 | 30 | 416.5 | 38.6 | 34.3 | 1627.95 | 1136.4 |
| 3 | 670 | 33 | 309.8 | 53.4 | 37 | 1789.23 | 1100.2 |
| 4 | 760 | 33 | 294.1 | 46.9 | 35.6 | 2026.86 | 1166.6 |
| 5 | 900 | 42 | 201.2 | 66.4 | 43.7 | 2401.93 | 1250.3 |
| 6 | 530 | 27 | 492.5 | 45.3 | 38 | 1416.78 | 1129.8 |
| 7 | 720 | 39 | 220.5 | 69.6 | 44.3 | 1925.02 | 1090.4 |
| 8 | 550 | 21 | 203.7 | 36.6 | 29 | 1467.14 | 837.3 |
| 9 | 970 | 45 | 9.2 | 29 | 59.4 | 2585.35 | 1152.7 |
| 10 | 670 | 72 | 321.7 | 67.7 | 41.2 | 1795.63 | 1166.6 |
| 11 | 560 | 51 | 245.8 | 39.7 | 27.4 | 1497.14 | 917.9 |
| 12 | 510 | 45 | 259 | 34.7 | 30.1 | 1363.72 | 872.8 |
| 13 | 715 | 60 | 183.3 | 63.8 | 45.8 | 1913.63 | 1054.5 |
| 14 | 690 | 72 | 127.6 | 72 | 57.2 | 1850.89 | 1067.8 |
| *Total* | 9505.00 | 600 | 3613.70 | 699.00 | 558.10 | 25,394.94 | - |
| *Average* | 678.93 | 42.86 | 258.12 | 49.93 | 39.86 | 1813.92 | 1073.54 |
| *C* | | | | 66,642.83 | | | |

## 5.3. Sensitivity analysis

The goal of this paper is to reduce carbon emissions and total costs. The speed and fixed cost of each truck is set in Section 5.1. To discuss the effect of these variables on the optimal solution, the following sensitivity analysis is done in this paper. The data in Table 6 is the average of 10 runs of the program. The data in Table 6 presents the number of trucks were used, the number of $CO_2$ emissions, the total costs respectively. $N$ represents the number of trucks were used, $W$ represents the number of $CO_2$ emissions, $C$ represents the total costs. Figure 7 presents the changing trend of total costs under different speeds and fixed costs of trucks.

**Table 6.** Sensitivity analysis on speed and fixed costs of trucks.

| $c_k$ / $v$ | 200 | | | 300 | | | 400 | | |
|---|---|---|---|---|---|---|---|---|---|
| | *N* | *W* | *C* | *N* | *W* | *C* | *N* | *W* | *C* |
| 45 | 19 | 25,411.91 | 66,448.73 | 17 | 25,091.86 | 66,961.78 | 17 | 25,442.98 | 69,525.13 |
| 50 | 16 | 25,232.85 | 65,408.45 | 16 | 24,446.39 | 66,774.66 | 17 | 25,424.42 | 69,479.49 |
| 55 | 15 | 24,758.93 | 64,043.15 | 16 | 24,681.15 | 66,651.89 | 15 | 24,510.98 | 66,433.51 |
| 60 | 14 | 24,382.16 | 62,916.72 | 14 | 25,394.94 | 66,642.83 | 14 | 24,652.60 | 66,381.69 |
| 65 | 13 | 24,353.64 | 62,646.59 | 14 | 24,172.63 | 63,801.50 | 14 | 24,243.58 | 65,375.96 |
| 70 | 13 | 24,054.36 | 61,919.53 | 13 | 23,984.38 | 63,038.63 | 13 | 23,771.99 | 63,816.39 |
| 75 | 13 | 23,774.60 | 61,222.80 | 11 | 22,803.29 | 59,534.49 | 11 | 22,803.29 | 59,534.49 |
| *mean* | - | 24,566.92 | 63,515.14 | - | 24,367.81 | 64,772.25 | - | 24,407.12 | 65,792.38 |

According Table 6 and Figure 7, we can find that as the fixed costs increase, so does the total costs. Under a fixed cost of the truck, as the speed of the truck increases, the number of trucks used decreases and the total costs decrease. In order to ensure the safety of transportation, the speed of each truck is usually controlled between 55 and 65(unit: km/h). This paper takes the intermediate value and assumes the speed of the truck is 60 km/h.

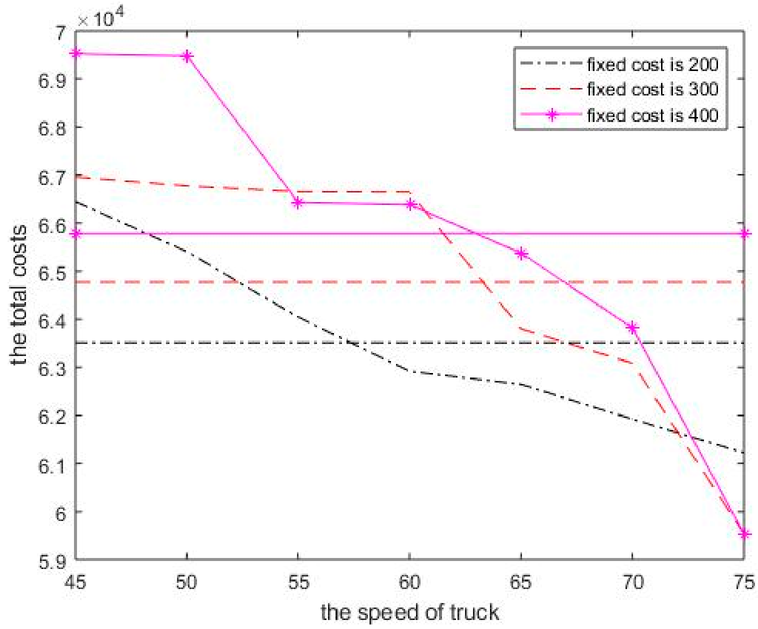


**Figure 7.** The changing trend in total costs under different speeds and fixed costs of trucks.

### 5.4. Comparative Analysis of Calculation Examples

Based on the HGAVNS solves the scheduling scheme of trucks between outer yard and multiple terminals considering carbon emissions under TAS. To verify the effectiveness of TAS, the following comparative experiment was conducted in this paper. Assume that the terminal establishes TAS, the outer yard doesn't adopt TAS. Appendix A Table A2 shows the scheduling scheme without TAS. In Table A2, the order 1–13 in the first row represents the delivery service order of relevant trucks. This paper assumes $f$ represents the waiting time of the truck outside the first terminal. $g$ represents the waiting time of the truck outside the second terminal. The first nine trucks and the first five delivery services of the tenth truck diver 40 ft containers. The delivery and operation conditions of these trucks are marked by $1 \times 4$ array. The $1 \times 4$ array's form is $(a, c, d, f)$. The last delivery service of the tenth truck and the last five trucks diver 20 ft containers. Which were marked with shadow are the operating conditions of a truck loading two 20 ft containers going to two terminals at the same time. These are marked by $1 \times 6$ array. The $1 \times 6$ array's form is $([a, a], b, [c, c], d, f, g)$. Which weren't marked with shadow are the operating conditions of a truck loading one or two 20 ft containers going to one terminal. These are marked by a $1 \times 5$ array. The $1 \times 5$ array's form is $(a, b, c, d, f)$.

The data in Table 7 presents the transportation mileage, working time, carbon emissions and the returning time in the last delivery of each truck without TAS. $T_{w1}$ represents the total waiting time outside the first terminal. $T_{w2}$ represents the total waiting time outside the second terminal.

The scheduling scheme under the traditional model needs 15 trucks. The total costs are 68,512.51. The maximum delivery number of a truck is 13 times. The longest mileage of most trucks is 860 km. The average waiting time outside first terminal is 132.24 min. The average waiting time outside second terminal is 26.25 min. The average waiting time at terminal gate is 51.70 min. The average operating time inside terminal is 49.15 min. The average return time in the last delivery is 900.38 min. The average carbon emissions of a truck is 1696.66 kg. Compared with the data of optimal scheduling scheme under TAS in Table 5, the number of trucks is 14. The total costs are 66642.83. The maximum delivery number of a truck is 14 times. The longest mileage of most trucks is 970 km. The average waiting time at outer yard is 258.12 min. The average waiting time at terminal gate is 49.93 min. The average operating time inside terminal is 39.86 min. The average return time in the last delivery is 1073.54 min. The average carbon emissions of a truck is 1813.92 kg.

**Table 7.** Operation information of optimal scheduling scheme without TAS.

| No. | $d$/km | $T_l$/min | $T_{w1}$/min | $T_{w2}$/min | $T_q$/min | $T_o$/min | $EM$/kg | $T_r$/min |
|---|---|---|---|---|---|---|---|---|
| 1 | 350 | 15 | 317 | - | 36 | 42 | 937.85 | 737 |
| 2 | 710 | 39 | 207 | - | 84.7 | 51 | 1900.94 | 1088.7 |
| 3 | 860 | 39 | 0 | - | 71 | 44.4 | 2296.18 | 1011.4 |
| 4 | 620 | 30 | 62.6 | - | 53 | 54.2 | 1658.27 | 796.8 |
| 5 | 800 | 33 | 0 | - | 60.6 | 42 | 2135.09 | 932.6 |
| 6 | 730 | 33 | 230 | - | 67.2 | 45.3 | 1950.69 | 1102.5 |
| 7 | 710 | 36 | 30.5 | - | 67.8 | 43.3 | 1897.87 | 884.6 |
| 8 | 620 | 27 | 163.2 | - | 52.9 | 56.5 | 1658.18 | 896.6 |
| 9 | 630 | 33 | 204.2 | - | 66.3 | 44 | 1685.45 | 974.5 |
| 10 | 460 | 27 | 230 | 0 | 38.4 | 45.2 | 1231.31 | 784.2 |
| 11 | 690 | 66 | 0 | 0 | 44 | 53.4 | 1846.69 | 810.4 |
| 12 | 540 | 60 | 290.7 | 0 | 38.8 | 54.9 | 1448.11 | 947.4 |
| 13 | 560 | 54 | 146.6 | 0 | 28 | 44.8 | 1498.11 | 823.4 |
| 14 | 575 | 54 | 22.1 | 84.6 | 34.2 | 68.2 | 1607.41 | 825.1 |
| 15 | 600 | 54 | 79.7 | 72.9 | 32.6 | 48.1 | 1697.74 | 890.5 |
| *Total* | 9455.00 | 600.00 | 1983.60 | 157.50 | 775.50 | 737.3 | 25,449.89 | - |
| *Average* | 630.33 | 40.00 | 132.24 | 26.25 | 51.70 | 49.15 | 1696.66 | 900.38 |
| *C* | | | | | 68,512.51 | | | |

In terms of the number of trucks used in the scheduling scheme, the new scheduling model under TAS is 14. Use one less truck than the traditional scheduling scheme without TAS. Under TAS, the total costs were reduced by 2.73%, and the carbon emissions were reduced by 0.22%.

In terms of the working time, that the total queue time of the trucks decreases from 775.5 min to 699 min after TAS is adopted. The maximum queue time decreased from 84.7 min to 72 min. The average queue time decreases from 51.7 min to 49.93 min. The total operation time of the trucks decreases from 737.3 min to 558.1 min after TAS is adopted. The maximum operation time decreased from 68.2 min to 59.4 min. The average operation time decreases from 49.15 min to 39.86 min. It can be seen that the TAS can effectively reduce the queue time and the operation time, improve work efficiency. Figures 8 and 9 respectively compare the queue time of trucks and the operation time at terminal under TAS and without TAS.

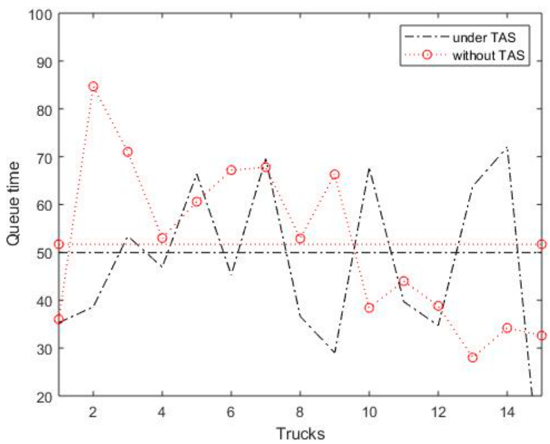


**Figure 8.** Queue time comparison.

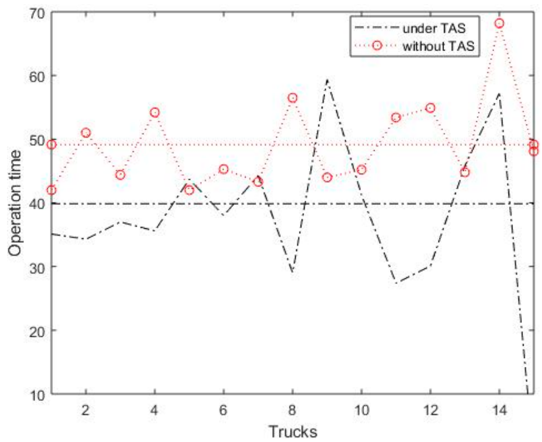


**Figure 9.** Operation time comparison.

In terms of the waiting time, under TAS, the waiting time of a truck is mostly generated at the outer yard. When trucks wait at the outer yard, there are no costs. Without TAS, trucks haven't appointment information communication, trucks will depart from the outer yard immediately after the last delivery completed. However, often it arrived at the terminal due to terminal in a variety of reasons need to wait for a long time outside the terminal, there will be opportunity loss costs.

Compared with the traditional scheduling scheme, the scheduling scheme under TAS need one less truck, improves the delivery efficiency of trucks, effectively reduces energy consumption, and finally reduces the total costs of the truck company.

## 6. Conclusions

In this paper, the scheduling problem of trucks between the outer yard and multiple terminals under the TAS is solved by a hybrid genetic algorithm with a variable neighborhood search based on the corresponding optimization model and the consideration of carbon emissions. The numerical example and comparative analysis show the validity of the proposed model and algorithm. The truck fleet can be reasonably scheduled to complete the delivery tasks during each appointment period. The number of trucks used under TAS is one less than the traditional scheduling scheme, it improves the work efficiency of trucks. Fuel consumption and carbon emissions can be reduced greatly. Finally, the total costs of a truck company can be reduced. The research results expand the theoretical research on truck scheduling between the outer yard and multi-terminals.

In terms of practical application, the case analysis of terminal in China can provide some basis for the implementation of TAS and provide some references for the optimization decision of the truck company on truck scheduling.

It should be pointed out that because of the complexity of various links and influencing factors involved in the delivery, the queue rules of trucks at the terminal gate, relevant interference factors and trucks missing the appointment in the process of delivery were not considered in the solution and analysis, which should be further studied in the future.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** The optimal scheduling scheme of trucks under TAS.

| *No.* \ *Order* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (2,1,0,97) | (2,2,145.2,0) | (3,3,230.7,0) | (3,3,297.5,0) | (4,5,368.7,0) | (7,6,460.2,231.8) | (7,5,756.7,0) | (8,5,851.9,0) | (9,4,945.4,0) | (9,7,1008.2,0) | / | / | / | / |
| 2 | (2,1,0,97) | (3,3,143,64) | (3,3,273.8,0) | (4,5,345,0) | (7,6,436.5,255.5) | (7,5,756.7,0) | (8,7,851.9,0) | (9,6,935.9,0) | (9,4,998.8,0) | (10,7,1059,0) | / | / | / | / |
| 3 | (2,1,0,97) | (2,2,143,0) | (3,3,228.5,0) | (4,5,295.3,21.7) | (4,5,408.5,0) | (7,6,500.9,191.1) | (7,4,756.7,0) | (8,6,821.8,0) | (8,5,885.9,0) | (9,6,979.2,0) | (9,6,1042.1,0) | / | / | / |
| 4 | (1,2,0,0) | (2,2,87,0) | (2,2,174.4,0) | (3,3,259.9,0) | (3,3,326.7,0) | (7,6,397.9,294.1) | (7,5,756.7,0) | (8,5,851.9,0) | (9,7,945.4,0) | (9,4,1029,0) | (10,7,1089.2,0) | / | / | / |
| 5 | (1,2,0,0) | (2,2,87,0) | (2,2,174.4,0) | (3,1,259.9,0) | (4,5,306.9,10.1) | (4,5,408.5,0) | (7,6,500.9,191.1) | (7,4,756.7,0) | (8,4,821.8,0) | (8,7,884.9,0) | (9,6,969.3,0) | (9,6,1032.2,0) | (10,7,1093.3,0) | (11,7,1173.7,0) |
| 6 | (2,1,0,97) | (3,3,143,64) | (6,7,273.8,288.2) | (7,6,648.7,43.3) | (7,7,7567,0) | (8,6,843.7,0) | (8,7,907.8,0) | (9,4,992.2,0) | (10,7,1052.4,0) | / | / | / | / | / |
| 7 | (2,1,0,97) | (2,2,143,0) | (3,3,228.5,0) | (3,1,295.3,0) | (4,5,345.7,0) | (5,4,437.2,14.8) | (5,4,518,0) | (7,6,583.3,108.7) | (7,4,756.7,0) | (8,6,821.8,0) | (8,7,885.9,0) | (9,6,970.3,0) | (9,4,1033.2,0) | / |
| 8 | (1,2,0,0) | (2,2,87,0) | (4,5,174.4,142.6) | (4,5,408.5,.0) | (6,7,500.9,61.1) | (6,5,648.7,0) | / | / | / | / | / | / | / | / |
| 9 | (1,2,0,0) | (2,2,87,0) | (2,1,174.4,0) | (3,2,220.4,0) | (4,5,307.8,9.2) | (4,2,408.5,0) | (5,5,501,0) | (6,3,596.6,0) | (6,4,672.8,0) | / | / | / | / | / |
| 10 | (3,2,3,0,204) | (3,2,1,273.8,0) | (3,2,3.323.8,0) | (4,2,5,398,0) | (5,2,3,493.4,0) | (7,2,6,571.3,117.7) | (7,2,4,758.6,0) | (8,2,4,826.7,0) | (8,2,4,892.8,0) | (9,2,4,960.2,0) | (9,2,4,1026,0) | (10,2,7,1089.2,0) | / | / |
| 11 | (1,1,2,0,0) | (2,2,1,87,7) | (2,2,2,144,0) | (3,2,3,232.5,0) | (3,2,1,302.3,0) | (4,2,5,355.7,0) | (7,2,6,450.2,238.8) | (7,2,5,758.6,0) | (8,2,6,856.8,0) | / | / | / | / | / |
| 12 | (2,1,1,0,97) | (2,2,2,145.2,0) | (3,2,3,233.7,0) | (3,2,2,303.5,0) | (6,2,7,397,162) | (6,2,4,645.8,0) | (7,2,6,712.9,0) | (7,2,5,780.6,0) | / | / | / | / | / | / |
| 13 | (2,1,1,0,97) | (2,2,2,145.2,0) | (3,2,1,233.7,0) | (3,2,2,283.7,0) | (4,2,2,377.2,0) | (6,2,7,472.7,86.3) | (6,2,3,645.8,0) | (7,2,5,723.8,0) | (8,1,7,821.4,0) | (9,2,4,928.5,0) | (9,2,4,994.3,0) | / | / | / |
| 14 | (2,1,1,0,97) | (2,2,2,145.2,0) | (3,2,1,233.7,0) | (3,1,3,283.7,0) | (5,2,4,415.4,30.6) | (5,2,4,516,0) | (6,2,7,584.3,0) | (6,2,4,674,0) | (7,2,4,741.1,0) | (8,2,4,807.4,0) | (8,2,4,873.5,0) | (9,2,4,940.9,0) | (9,2,6,1006.7,0) | / |

**Table A2.** The optimal scheduling scheme of truck without TAS.

| *No.* \ *Order* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (4,5,0,317) | (4,5,408.5,0) | (5,4,500.9,0) | (6,7,566.9,0) | (6,7,653.6,0) | / | / | / | / | / | / | / | / |
| 2 | (3,3,0,207) | (3,1,278.2,0) | (4,3,328.6,0) | (4,3,400.2,0) | (5,5,473.2,0) | (6,7,569.4,0) | (6,1,656.1,0) | (7,6,709,0) | (7,4,773.7,0) | (8,6,838.8,0) | (8,6,902.9,0) | (9,6,967.7,0) | (9,6,1030.6,0) |
| 3 | (1,2,0,0) | (2,2,87,0) | (2,2,174.4,0) | (3,3,259.9,0) | (4,2,326.7,0) | (4,3.418,0) | (5,5,491,0) | (6,7,587.2,0) | (6,4,673.9,0) | (10,6,738,0) | (8,7,802.7,0) | (8,6,886.7,0) | (9,6,951.5,0) |
| 4 | (1,2,0,0) | (2,1,87,10) | (2,1,145.2,0) | (2,2,193.4,0) | (4,5,278.9,38.1) | (4,3,408.5,0) | (5,4,481.5,0) | (6,7,547.5,14.5) | (6,7,648.7,0) | (7,6,735.1,0) | / | / | / |
| 5 | (1,2,0,0) | (2,2,87,0) | (2,2,174.4,0) | (3,2,259.9,0) | (4,5,350.4,0) | (5,5,441.9,0) | (5,5,538.1,0) | (6,7,633.7,0) | (7,6,720.1,0) | (7,6,784.8,0) | (8,7,851.6,0) | / | / |
| 6 | (1,2,0,0) | (4,5,87,230) | (4,3,408.5,0) | (5,5,481.5,0) | (6,7,577.7,0) | (6,4,664.4,0) | (7,7,728.5,0) | (8,7,814,0) | (8,7,898,0) | (9,6,982.4,0) | (9,4,1045.3,0) | / | / |
| 7 | (1,1,0,0) | (2,1,87,10) | (2,1,145.2,0) | (3,3,193.4,0) | (3,2,273.8,0) | (4,5,364.3,0) | (7,4,455.8,0) | (5,4,521.8,0) | (6,5,587.1,0) | (7,6,685.1,6.9) | (7,6,756.7,0) | (8,6,823.5,0) | / |
| 8 | (1,2,0,0) | (3,3,87,120) | (4,5,273.8,43.2) | (4,5,408.5,0) | (5,5,500.9,0) | (6,7,596.5,0) | (7,7,683.2,0) | (7,6,768.7,0) | (8,6,768.7,0) | / | / | / | / |
| 9 | (2,1,0,97) | (3,3,143,64) | (4,5,273.8,43.2) | (4,5,408.5,0) | (5,4,500.9,0) | (5,4,566.9,0) | (6,4,632.2,0) | (7,7,696.3,0) | (7,6,781.8,0) | (8,6,848.6,0) | / | / | / |
| 10 | (1,2,0,0) | (4,5,87,230) | (4,5,408.5,0) | (5,5,500.9,0) | (6,1,596.5,0) | (6,2,4,649.4,0) | (7,2,6,716.5,0) | / | / | / | / | / | / |
| 11 | (1,2,2,0,0) | (2,2,1,97,0) | (2,2,1,148.2,0) | (3,2,5,199.4,0) | (3,2,5,290,0) | (4,2,4,384.4,0) | (5,2,7,448.9,0) | (5,2,4,538.5,0) | (6,2,4,606.8,0) | (6,2,6,675.6,0) | (7,2,4,744.1,0) | / | / |
| 12 | (1,2,1,0,0,0) | (2,2,1,50,44) | (2,2,3,145.2,0) | (4,2,3,214,110) | (5,2,4,398.6,81.4) | (5,2,4,518,0) | (6,2,7,586.3,0) | (7,2,6,676,13) | (8,2,7,756.7,42.3) | (8,2,4,886,0) | / | / | / |
| 13 | (1,2,2,0,0) | (2,2,2,90,0) | (2,2,1,170.4,0) | (3,2,3,219.4,0) | (4,2,5,289.2,24.8) | (5,2,4,408.5,40.5) | (6,2,7,518,41) | (7,2,4,648.7,40.3) | (7,2,4,755.3,0) | / | / | / | / |
| 14 | (1,2,2,0,0) | ([2,3],2,[2,3],90,0,84.6) | (3,2,3,273.8,0) | (4,2,3,348,0) | (5,2,5,422.6,11.4) | (5,2,3,533.2,0) | (6,2,4,611.2,0) | (7,2,4,678.3,10.7) | (7,2,6,755.3,0) | / | / | / | / |
| 15 | (1,2,2,0,0) | (2,2,1,90,4) | (2,2,2,145.2,0) | (3,2,2,233.7,0) | (4,2,5,324.1,0) | ([5,6],2,[1,7],418.6,35.4,72.9) | (7,2,4,648.7,40.3) | (7,2,4,755.3,0) | (8,2,6,823.4,0) | / | / | / | / |

## References

1. Kot, S.; Goldbach, I.R.; Ślusarczyk, B. Supply Chain Management in SMEs-Polish and Romanian Approach. *Econ. Sociol.* **2018**, *11*, 142–156. [CrossRef]
2. Kot, S. Cost structure in relation to the size of road transport enterprises. *Promet* **2015**, *27*, 387–394. [CrossRef]
3. Schulte, F.; González, R.G.; Voß, S. Reducing Port-Related Truck Emissions: Coordinated Truck Appointments to Reduce Empty Truck Trips. In *International Conference on Computational Logistics*; Springer: Berlin, Germany, 2015; pp. 495–509.
4. Wang, X. Changes in $CO_2$ Emissions Induced by Agricultural Inputs in China over 1991–2014. *Sustainability* **2016**, *8*, 414. [CrossRef]
5. Huynh, N. Methodologies for Reducing Truck turn Time at Maritime Container Terminals. Ph.D. Thesis, The University of Texas at Austin, Austin, TX, USA, 2005.
6. Morais, P.; Lord, E. *Terminal Appointment System Study*; Transport Canada: Ottawa, ON, USA, 2006.
7. Wu, D.; Ran, Y.C. Exploration and practice of container appointment congregation. *Port. Econ.* **2012**, *3*, 5–9.
8. Torkjazi, M.; Hunnh, N.; Shiri, S. Truck appointment systems considering impact to drayage truck tours. *Transp. Res. Part E Logist. Transp. Rev.* **2018**, *116*, 208–228. [CrossRef]
9. Chen, G.; Govindan, K.; Golias, M.M. Reducing truck emissions at container terminals in a low carbon economy: Proposal of a queueing-based bi-objective model for optimizing truck arrival pattern. *Transp. Res. Part E Logist. Transp. Rev.* **2013**, *55*, 3–22. [CrossRef]
10. Chen, X.; Zhou, X.; List, G.F. Using Time-varying Tolls to Optimize Truck Arrivals at Ports. *Transp. Res. Part E Logist. Rev.* **2011**, *47*, 965–982. [CrossRef]
11. Huynh, N.; Walton, C.M. Improving efficiency of drayage operations at seaport container terminals through the use of an appointment system. In *Handbook of Terminal Planning*; Böse, J.W., Ed.; Springer: New York, NY, USA, 2011; pp. 323–344.
12. Zhang, X.; Zeng, Q.; Chen, W. Optimization Model for Truck Appointment in Container Terminals. *Procedia-Soc. Behav. Sci.* **2013**, *96*, 1938–1947. [CrossRef]
13. Chen, G.; Govindan, K.; Yang, Z.Z.; Choi, T.M.; Jiang, L. Terminal Appointment System Design by Nonstationary M(t)/Ek/c(t) Queueing Model and Genetical Algorithm. *Int. J. Prod. Econ.* **2013**, *146*, 694–703. [CrossRef]
14. Zehendner, E.; Feillet, D. Benefits of a truck appointment system on the service quality of inland transport modes at a multimodal container terminal. *Eur. J. Oper. Res.* **2014**, *235*, 461–469. [CrossRef]
15. Namboothiri, R.; Erera, A.L. Planning local container drayage operations given a port access appointment system. *Transp. Res. Part E Logist. Transp. Rev.* **2008**, *44*, 185–202. [CrossRef]
16. Islam, S.; Olsen, T. Truck-sharing challenges for hinterland trucking companies: A case of the empty container truck trips problem. *Bus. Process Manag. J.* **2014**, *20*, 290–334. [CrossRef]
17. Schulte, F.; Lalla-Ruiz, E.; González-Ramírez, R.G.; Voß, S. Reducing port-related empty truck emissions: A mathematical approach for truck appointments with collaboration. *Transp. Res. Part E Logist. Transp. Rev.* **2017**, *105*, 195–212. [CrossRef]
18. Phan, M.; Kim, K.H. Collaborative truck scheduling and appointments for trucking companies and container terminals. *Transp. Res. Part B Methodol.* **2016**, *86*, 37–50. [CrossRef]
19. Chen, G.; Govindan, K.; Yang, Z. Managing truck arrivals with time windows to alleviate gate congestion at container terminals. *Int. J. Prod. Econ.* **2013**, *141*, 179–188. [CrossRef]
20. Niu, B.; Xie, T.; Tan, L.; Bi, Y.; Wang, Z. Swarm Intelligence Algorithms for Yard Truck Scheduling and Storage Allocation Problems. *Neurocomputing* **2016**, *188*, 284–293. [CrossRef]
21. Zhang, X.; Zeng, Q.; Yang, Z. Optimization of truck appointments in container terminals. *Marit. Econ. Logist.* **2019**, *21*, 125–145. [CrossRef]
22. Sim, J. A carbon emission evaluation model for a container terminal. *J. Clean. Prod.* **2018**, *186*, 526–533. [CrossRef]
23. Heilig, L.; Lalla-Ruiz, E.; Voß, S. Multi-objective inter-terminal truck routing. *Transp. Res. Part E Logist. Transp. Rev.* **2017**, *106*, 178–202. [CrossRef]
24. Heilig, L.; Lalla-Ruiz, E.; Voß, S. port-IO: An integrative mobile cloud platform for real-time inter-terminal truck routing optimization. *Flex. Serv. Manuf. J.* **2017**, *29*, 503–534. [CrossRef]

25. Yu, H.; Ge, Y.E.; Chen, J.; Luo, L.; Tan, C.; Liu, D. $CO_2$ emission evaluation of yard tractors during loading at container terminals. *Transp. Res. Part D Transp. Environ.* **2017**, *53*, 17–36. [CrossRef]
26. Li, N.; Chen, G.; Govindan, K.; Jing, Z. Disruption management for truck appointment system at a container terminal: A green initiative. *Transp. Res. Part D Transp. Environ.* **2018**, *61*, 261–273. [CrossRef]
27. He, J.; Huang, Y.; Yan, W.; Wang, S. Integrated internal truck, yard crane and quay crane scheduling in a container terminal considering energy consumption. *Expert Syst. Appl.* **2015**, *42*, 2464–2487. [CrossRef]
28. Wang, H.; Al-Saadi, I.; Lu, P.; Jasim, A. Quantifying greenhouse gas emission of asphalt pavement preservation at construction and use stages using life-cycle assessment. *Int. J. Sustain. Transp.* **2019**, *13*, 1–10. [CrossRef]
29. Tolliver, D.; Lu, P.; Benson, D. Railroad energy efficiency in the United States: Analyticla and statistical analysis. *J. Transp. Eng.* **2014**, *140*, 23–30. [CrossRef]
30. Xiao, Y.; Zhao, Q.; Kaku, I.; Xu, Y. Development of a fuel consumption optimization model for the capacitated vehicle routing problem. *Comput. Oper. Res.* **2012**, *39*, 1419–1431. [CrossRef]
31. Lu, P.; Tolliver, D. Multiobjective transportation preservation decision making. *J. Transp. Eng.* **2013**, *139*, 880–888. [CrossRef]