Modeling and Analyses of Container Drayage Transportation Problem with the Objective of Low Carbons

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Abstract: A container drayage transportation problem with the objective of decreasing carbon emissions during transportation is researched. Based on a determined-activities-on-vertex (DAOV) graph, a mixed-integer linear programming model of the drayage transportation problem is established. The speed and precision of solving this model using LINGO are tested. This model is also compared with traditional models which minimize the total working time. The effects of the width of time windows, the ratio of inbound containers and the ratio of empty containers are analyzed. The results indicate that this method could decrease carbon emissions significantly and hence has important academic meanings.

1 INTRODUCTION

Freight transportation is a main source of greenhouse gas emissions including the emissions of carbon dioxide. The carbon emission from road freight transportation has a large ratio among that from freight transportation. A report by the UN Intergovernmental Panel on climate change said that [1]: over the past 50 years, greenhouse gases emissions into the atmosphere were the main reason of the rising of the average global temperatures, and global warming will cause sea levels rising，frequency of extreme weather and other adverse natural phenomena, thus affect the human production, life and even threaten the survival of mankind further. Logistics and transport industry is a part of the main sources of greenhouse gases such as CO_2. While the CO_2 emissions of road freight are the important proportion of the total CO_2 emissions in the logistics transportation. At present, container is the main form of freight transportation. Therefore, container transportation by road is an important aspect of road freight transport. Thus, research on container transportation by road with the objective of low carbon will be friendly to the environment.

Usually, containers are mainly transported by vessels or by trains at a long distance level and performed by trucks at a short distance level. We call the segment of transportation by trucks between customers and terminals as drayage. Container drayage transportation can provide door-to-door services. Although the transportation distances by trucks are short, the total costs per TEU (Twenty foot Equivalent Unit) per kilometer are relatively high. Moreover, this transportation mode is the key source of road congestion, shipment delays, and disruptions. Therefore, it is extremely important to improve the efficiency of container transportation [2].

This paper studies a container drayage problem. We not only consider the time windows attributes of the transportation task and empty containers reposition, but also consider the effects of the container drayage transportation on the environment. Based on an extension of determined-activities-on vertex (DAOV) graph [3], we use the total carbon emissions of trucks in container drayage transportation instead of the traditional objective function that takes the total travelling time of trucks or the drayage operation costs as the objective function, and establish a mixed integer linear programming model. Then we also analyze the effect of some key parameters of container drayage transportation problem on carbons emissions.

The remaining content of this paper is organized as follows. The container drayage problem with the objective of low carbons is described in Section 2, mathematically modeled based on a formulated directed graph in Section 3, and validated and analyzed using a number of randomly generated instances in Section 4. The conclusions are presented in Section 5.

2 CONTAINER DRAYAGE PROBLEM WITH OBJECTIVE OF LOW CARBONS

2.1 Problem Definition

A container transport enterprise provides container drayage transportation services for customers in a local area. The enterprise has a port and a depot. The depot is for parking trucks and stacking empty containers. The drayage services include both the explicitly required transportation of containers between customer locations and a port as well as the implicitly required repositioning of empty containers between customer locations, the port and the depot. There are time windows in the port and customers. Corresponding activities must be started in the given time windows. If a truck arrived at the port or customer ahead of time, it can

This work is supported by the National Science Foundation for Distinguished Young Scholars of China under Grant No. 71325002, No. 61225012; the National Natural Science Foundation of China under Grant No.71071028, No.71471034; the Fundamental Research Funds for State Key Laboratory of Synthetical Automation for Process Industries under Grant No.2013ZCX11; Key Laboratory of Networked Control System, Shenyang Institute of Automation Chinese Academy of Sciences under Grant No.WLHKZ2014008.

wait. The depot is owned to the enterprise, so it can be visited by trucks at any time.

There are four types of container drayage tasks. When a customer has a number of goods which need to be transported to other areas, an empty container is required to be delivered to the customer. After the goods are packed, the full container is delivered to the port. This task is called outbound full container (OF). Similarly, a full container initially located in the port needs to be transported to a customer, and then an empty container is released and ready to be reused after it is unloaded and unpacked. This task was called inbound full container (IF). In addition, because of the trade imbalance between areas, the region may appear a surplus or shortage of large number of empty containers. it needs to be a certain amount of empty container transport to the port (they are prepared to be transported to other regions), this is called outbound empty container (OE); or it needs import a certain amount of empty container (they can be shipped to the yard or directly used for export goods), this is called inbound empty container (IE).

Therefore, the drayage container transportation problem studied in this paper is that: how to schedule the trucks and determine the handling sequence and time of each task visited to complete the transport plan in a given period (usually a day) to minimize the total carbon emissions.

Basic assumptions and the parameters are shown in Section 2.2 and Section 2.3, respectively.

2.2 Assumptions

(1) All the information of the transport tasks is known at the beginning of the time horizon.
(2) Each full container transport task refers to one customer and each task only involves transporting one container.
(3) All container and trucks are homogenous.
(4) Each truck travels at an economic speed in given road condition.

2.3 Parameters

n: initial number of trucks parked at the depot.

$C = C_{OF} \cup C_{IF} \cup C_{OE} \cup C_{IE}$: transport tasks set in given period. 'C_{OF}', 'C_{IF}', 'C_{OE}', 'C_{IE}' represent container transportation sets of inbound full, outbound full, inbound empty and outbound empty containers, respectively.

$[\tau_i^A, \tau_i^B]$: the first time window of task $i \in C(\tau_i^A \leq \tau_i^B)$.

$[\tau_i^C, \tau_i^D]$: The second time window of task $i \in C(\tau_i^C \leq \tau_i^D)$.

$t_{i,j}$: truck travelling time from location i to j. Where, $i(\text{or } j) = -1$ represents "port", and $i(\text{or } j) = 0$ represents "depot". $i(\text{or } j) > 0$ represents "customer" $i(\text{or } j) \in C_{IF} \cup C_{OF}$. $t_{i,j} \geq 0$, $t_{i,j} = t_{j,i}$.

t_i: time of packing the container or getting goods out of the container of task $i \in C_{IF} \cup C_{OF}$.

t: time to pick up or drop off a container.

m_0: mass of a truck

m_1: total mass of a truck plus an empty container.

3 MATHEMATICAL MODEL

Based on an extension of the DAOV graph by introducing an attribute of arcs - carbons emissions, a mixed-integer linear programming model for the drayage transportation problem is established.

3.1. DAOV Graph Definition

Let asymmetric graph$G = \{V, A\}$ to formulate the problem, where $V = \{0\} \cup V_C$,'0' is a start/return vertex, V_C is the tasks vertices set, and $A = \{(i,j) | i = 0, j \in V_C; or\ i \in V_C, j \in V\}$.

Definition 1. A start/return vertex '0' is defined as the initial start from and final return to the depot [3].

Definition 2. A task vertex $i \in V_C$ is defined as the continuous determinate activities involved in the transportation of task $i \in C$.

Definition 3. An arc$(i,j) \in A$ is defined as the transfer of a truck from vertex i to vertex j.

The start/return vertex includes no actual activities. Each task vertex $i \in V_C$ is corresponding to one transportation task $i \in C$.It involves that a truck carries a full container between customers and the port, and the related packing, unpacking, loading and unloading a container, Where $V_C = V_{OF} \cup V_{IF} \cup V_{OE} \cup V_{IE}$.

Activities of arc (i,j) include bringing an empty container back to the depot, taking an empty container away from the depot, loading on an empty container travelling among customers and port. Detail description can be seen in [2][3]. What the difference in this paper is that empty task vertex $i \in V_E$ includes no actual activities. The related activities, loading/unloading an empty container are removing to its connecting arcs, Where $V_E = V_{OE} \cup V_{IE}$.

3.2. DAOV Graph Attributes

Attribute 1. The number of trucks initially packing in the depot $\boldsymbol{n}$ is the attribute of start/return vertex [3].

Attribute 2. The time period when the activities of task $i \in V_C$ can be started is the time window attribution of vertex $i \in V_C$, which is denoted by $[T_i^A, T_i^B](T_i^A \leq T_i^B)$ [3].

Attribution 3. The time spending on vertex $i \in V_C$ is the service time attribution of vertex $i \in V_C$, which is denoted by T_i[3].

If a transportation task contains two time windows, we can take its first time window as the time window of the corresponding vertex. In the same time, 'correct' the first time window according to the duration time of the activities in the first time window and the second time window. Thus, we can get the time window attribute and service time attribute of the task vertex.

The detail description of T_i^A, T_i^B, T_i can be shown as formula (1), (2), (3), respectively.

Attribute 4. The time of activities spending on arc (i,j) is the transfer time attribution of arc (i,j) denoted by T_{ij} [3]. T_{ij} can be calculated as formula (4).

Attribute 5. The carbons emissions of activities on arc (i,j) is the carbons emissions attribution of arc (i,j) denoted by Q_{ij}. Q_{ij} can be described as formula (5).

$$T_i^A = \begin{cases} \min\left(\max\left(\tau_i^A, \tau_i^C - t - t_{-1,i}\right), \tau_i^B\right), & i \in V_{IF} \\ \min\left(\max\left(\tau_i^A, \tau_i^C - t_i - t - t_{i,-1}\right), \tau_i^B\right), & i \in V_{OF} \\ \tau_i^A, & i \in V_E \end{cases} \quad (1)$$

$$T_i^B = \begin{cases} \min\left(\tau_i^B, \tau_i^D - t - t_{-1,i}\right), & i \in V_{IF} \\ \min\left(\tau_i^B, \tau_i^D - t_i - t - t_{i,-1}\right), & i \in V_{OF} \\ \tau_i^B, & i \in V_E \end{cases} \quad (2)$$

$$T_i = \begin{cases} \max\left(\tau_i^C - \tau_i^B, t + t_{-1,i}\right) + t + t_i, & i \in V_{IF} \\ \max\left(\tau_i^C - \tau_i^B, t_i + t + t_{-1,i}\right) + t, & i \in V_{OF} \\ 0, & i \in V_E \end{cases} \quad (3)$$

$$T_{ij} = \begin{cases} t_{0,-1}, & i = 0, j \in V_I; \text{ or } i \in V_O, j = 0 \\ t_{0,j} + 2t, & i = 0, j \in V_{OF} \\ t_{0,-1} + 2t, & i = 0, j \in V_{OE}; \text{ or } i \in V_{IE}, j = 0 \\ t_{i,0} + 2t & i \in V_{IF}, j = 0 \\ t_{i,0} + t_{0,-1} + 2t, & i \in V_{IF}, j \in V_I \\ t_{i,j} + 2t, & i \in V_{IF}, j \in V_{OF} \\ t_{i,-1} + 2t, & i \in V_{IF}, j \in V_{OE} \\ t_{-1,j} + 2t, & i \in V_{IE}, j \in V_{OF} \\ 0, & i \in V_O, j \in V_I; \text{ or } i \in V_{IE}, j \in V_{OE} \\ t_{-1,0} + t_{0,j} + 2t, & i \in V_O, j \in V_{OF} \\ 2t_{-1,0} + 2t, & i \in V_O, j \in V_{OE}; \text{ or } i \in V_{IE}, j \in V_I \end{cases} \quad (4)$$

$$Q_{ij} = \begin{cases} \varphi_{0,-1}(0), & i = 0, j \in V_I; \text{ or } i \in V_O, j = 0 \\ \varphi_{0,j}(1), & i = 0, j \in V_{OF} \\ \varphi_{0,-1}(1), & i = 0, j \in V_{OE}; \text{ or } i \in V_{IE}, j = 0 \\ \varphi_{i,0}(1), & i \in V_{IF}, j = 0 \\ \varphi_{i,0}(1) + \varphi_{0,-1}(0), & i \in V_{IF}, j \in V_I \\ \varphi_{i,j}(1), & i \in V_{IF}, j \in V_{OF} \\ \varphi_{i,-1}(1), & i \in V_{IF}, j \in V_{OE} \\ \varphi_{-1,j}(1), & i \in V_{IE}, j \in V_{OF} \\ 0, & i \in V_O, j \in V_I; \text{ or } i \in V_{IE}, j \in V_{OE} \\ \varphi_{0,-1}(0) + \varphi_{0,j}(1), & i \in V_O, j \in V_{OF} \\ \varphi_{0,-1}(0) + \varphi_{0,-1}(1), & i \in V_O, j \in V_{OE}; \text{ or } i \in V_{IE}, j \in V_I \end{cases} \quad (5)$$

Where, $\varphi_{i,j}(z) = t_{i,j}\left(\alpha_{i,j} m_z v_{i,j} + \beta {v_{i,j}}^3\right), V_I = V_{IF} \cup V_{IE}, V_O = V_{OF} \cup V_{OE}$

The carbons emissions rate of a truck mainly depends on the fuel consumption rate of the truck. When the speed of a truck is greater than 40 km/h, the fuel consumption rate of the truck is approximately proportional to the tractive power of engine [4]. According to the analysis of [4], traction power can be calculation as (6).

$$P = mav + mgv\sin\theta + mgvf_r\cos\theta + 0.5 f_d D\rho v^3 \quad (6)$$

Where, m (kg) is the total mass of a truck, a(m/s^2) is the accelerated speed, v (m/s) is the speed of the truck, g(9.81m/s^2) is the gravitational constant, θ is the road angle. D (m^2)is the frontal surface area of the vehicle. ρ is the air density (kg/m^3). and f_r and f_d are the coefficients of rolling resistance and drag, respectively.

Therefore, according to the method of [4], carbons emissions, denoted by $\varphi_{i,j}$, of truck travelling from location i to j at the speed $v_{i,j}$ can be calculated as (7).

$$\varphi_{i,j} \approx t_{i,j}\left(\alpha_{i,j} m_{i,j} v_{i,j} + \beta {v_{i,j}}^3\right) \quad (7)$$

Where, $\alpha = g\sin\theta + gf_r\cos\theta$ is a road-related constant. $\beta = 0.5 f_d D\rho$ is a vehicle-related constant. m_{ij} and d_{ij} are the total mass (empty container plus carried load) and distance from location i to location j, respectively.

Thus, the carbons emissions attribute of arc (i,j) can be formulated as formula (5).

3.3. A Mixed Integer Linear Programming Formulation

The following decision variables are introduced.

$$x_{ij} = \begin{cases} 1, & \text{if arc } (i,j) \in A \text{ is include in the solution} \\ 0, & \text{otherwise} \end{cases}$$

y_i: time when the activity of task $i \in V_C$ is started.

The problem can be formulated as the following mixed integer programming (MIP) model based on graph G **(Model 1).**

$$\text{minimize } Q = \sum_{(i,j)\in A} Q_{ij} x_{ij} \quad (8)$$

s.t.

$$\sum_{j \in V_C} x_{0j} \le n \quad (9)$$

$$\sum_{j \in V} x_{ij} = \sum_{j \in V} x_{ji} = 1, \forall i \in V_C \quad (10)$$

$$T_i^A \le y_i \le T_i^B, \forall i \in V_C \quad (11)$$

$$y_i + T_i + T_{ij} - y_j \le (1 - x_{ij})M, \forall i \in V_C, j \in V_C \quad (12)$$

$$x_{ij} \in \{0,1\}, \quad \forall (i,j) \in A \quad (13)$$

$$y_i \in \mathbb{R}, \qquad \forall i \in V_C \quad (14)$$

Function (8) minimizes the total carbons emissions of the activities on the arcs of graph *G*. The activities on the task vertices of graph *G* are determined, so the carbons emissions of these activities are constants. Thus, the objective function (8) also minimizes the total carbons emissions of the container drayage transportation. Constraint (9) limits the number of trucks. Constraint (10) represents each task vertex can be exactly visited once. Constraint (11) makes the activities of each task must start in its time window. Constraint (12) updates the start time along the route, where *M* is a sufficiently large number. This constraint can eliminate the sub-tours among container vertices. Constraints (13) and (14) imply the types of variables.

4 NUMERICAL EXPERIMENTS

Model 1 is a mixed integer linear programming model. It can be solved by commercial software if time of solving is allowed. This section presents the validity of the Model 1 and its comparisons with the method of [3].

4.1 Experiments Set

All experiments of this research are implemented on a ThinkCentre personal computer with Intel® Core(TM) i7-2600 CPU @ 3.4GHz (Quad-core eight thread processors) and 3.00 GB of RAM memories. The model can be solved by commercial software Lingo 11.0. The memory limit of the model generator is set as 256MB. The limit on the running time is set as 600 s.

According to the typical case of a certain type of trucks and containers, let m_0=8400kg, m_1=12300kg. D=7 m^2. Following relevant references [4, 5, 6], ρ=1.225 kg/m^3, f_d=1, α and v are randomly generated among [0.09, 0.15] and [40, 100] (km/h), respectively. Following references [2,7], the number of tasks of a fleet is not more than 75. We use the method of [2, 3] to randomly generate several instances, and each instance has 75 tasks with time windows distributed in the range of 60-100 minutes.

4.2 Validation and Comparison

First of all, 10 examples (Example 1-10) are randomly generated and are solved by Lingo 11.0. The results indicate that this method is valid. It can obtain the optimal solution of the model in the average time of 20.9 seconds. The speed of solving can meet the need of real world. In these example solutions, a large number of "inbound container" and "outbound container" are visited by trucks alternately. This situation can effectively cut down the distances of ineffective transportation. Simultaneously, it can reduce the carbons emissions.

Furthermore, Model 1 is compared with Model 2 (Container drayage problem with the objective of minimizing total operation time). The objective function of Model 2 is formulated as

$$\text{minimize } T = \sum_{(i,j) \in A} T_{ij} x_{ij} \quad (15)$$

with constraints (9)-(14). The objective function (15) minimizes the total transfer time of arcs. While the total service time on vertices is constant, this function also minimizes aggregate operation time of trucks. We solve Model 2 in the same setting as model 1 and obtain the total carbons emissions of each instance shown in Table 1. Where, total carbons emissions of model 1 and model 2 are denoted by

Q_1 and Q_2, respectively, and λ=1. Compared with Model 2, average carbons emissions of Model 1 are reduced by 7.9%.

Table 1. Results of Model 1 and Comparisons with Model 2

Instances	Model 1		Model 2		$\frac{Q_2 - Q_1}{Q_2}$
	Time (s)	Q_1 (kWh)	Time (s)	Q_2 (kWh)	(%)
1	122	4392	22	4682	6.2
2	1	3797	1	4334	12.4
3	2	3822	8	4313	11.4
4	30	4692	30	5303	11.5
5	1	2743	2	3072	10.7
6	45	10081	62	10696	5.8
7	2	4974	1	5570	10.7
8	1	7328	2	7583	3.4
9	2	8106	4	8701	6.8
10	3	4197	3	4513	7.0
average	20.9	5413	13.5	5877	7.9

4.3 Sensitivity Analysis of Key Parameters

In this section, the method of sensitivity analysis is used for investigating some key parameters of container drayage problem with the objective of low carbons emission.

Above all, we analyze the effect of time window width on the total carbons emissions of drayage transportation problem. The width of the time window is randomly generated within the range 30 to 60 minutes (group 1), and cancel constrains of time windows (group 3). Other parameters remain unchanged. Average carbons emissions of 10 instances of these three groups experiments (the primary experiment is group 2) are shown in Table 2. Obviously, with the width of the time window increase, the rate of carbons emissions saving of Model 1 compared with

Table 2. Effects of the width of time windows

Group	Width (minutes)	$\overline{Q_1}$ (kWh)	$\overline{Q_2}$ (kWh)	$\frac{\overline{Q_2} - \overline{Q_1}}{\overline{Q_2}}$ (%)
1	$[30, 60]$	6570	6905	4.9
2	$[60, 120]$	5413	5877	7.9
3	No time window	1656	2173	23.8

Model 2 will increase. Here, 'Width' represents the width range of time window. $\overline{Q_1}$ and $\overline{Q_2}$ are average carbons emissions of Model 1 and Model 2.

Then, it discusses the effect of the proportional distribution of inbound and outbound containers on carbons emissions. We set the proportional distribution of types of tasks and generate 8 group experiments. Each group includes 10 randomly generated instances. Model 1 and Model 2 obtain the optimal solution in a short time. The results of these 9 groups (involve the primary group) experiments are shown in Figure 1.

In Figure 1 axis of abscissa represents the generated probability of outbound containers denoted by p_O . Accordingly, the generated probability of inbound container denoted by $1 - p_O$. It is obvious that when p_O is close to 0.5, the average number of required trucks is lower and Model 1 emits fewer carbons than Model 2. That is because it is easy for one outbound container task to match one inbound container when p_O is close to 0.5, and save carbons emissions and transportation costs.

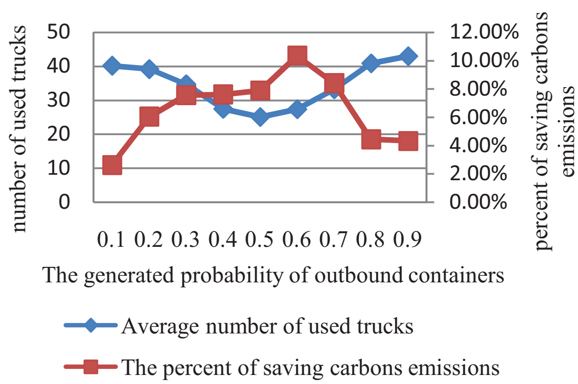

Fig 1. Effects of generated probability of outbound container on the number of trucks used and carbons emissions of Model 1saved

Finally, it analyzes the effect of generated probability of empty container on the number of trucks used and carbons emissions saved. We set the generated probability of empty container task to be 0.1, 0.2, 0.3, respectively, and other settings remain unchanged as section 4.1. Then three groups experiments are generated and each group includes 10 instances. The results based on Model 1 and Model 2 are shown in Table 3. It indicates that with the increase of the generated probability of empty container tasks, the number of trucks used decreases, and the carbons emissions of Model 1 saved increase, too. That is because an empty container task has no determined location of customer, so the room of decision making is large and it can get more good solutions.

Table 3. Effect of generated probability of empty container on the number of trucks used and carbon emissions saved

Group	p_E	K	$\frac{\overline{Q_2}-\overline{Q_1}}{\overline{Q_2}}$（%
1	0.1	26	7.9
2	0.2	24	7.6
3	0.3	20	9.6

5 CONCLUSIONS

Aiming to the distinguishing feature of two attributions of freight and transportation resource and considering the effect of transportation on the environment, a container drayage transportation problem is studied. Based on an extension of DAOV graph, the problem is proposed a mixed integer linear programming model. A large number of experiments are tested. The results suggest that this model can be solved quickly by Lingo if the scale of tasks is realistic size. Moreover, the comparison of the model with the objective of minimizing total operation time indicates that the mode with the objective of low carbons emissions can save carbons emissions effectively. Last, we analyze some key parameters including the width of the time window, the ratio of inbound containers and the ratio of empty containers.

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