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A time-space network based international transportation scheduling problem incorporating CO_2 emission levels

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Abstract: Environmental problems have received a great deal of attention in recent years. In particular, CO_2 emissions worsen global warming and other environmental problems. The transport sector accounts for 20% of the total CO_2 emissions. Therefore, the CO_2 emission reduction of the transport sector is of great importance. In order to reduce emissions effectively, it is necessary to change the distribution and transportation processes. The purpose of this study is to minimize both the transportation costs and CO_2 emissions during transportation. Our model considers a transportation scheduling problem in which loads are transported from an overseas production base to three domestic demand centers. The need for time-space networks arises naturally to improve the model. It is possible to know the distance carriers are moving, and also consider the timetables of carriers during transportation. Carrier choice, less-than carrier load, and domestic transportation among demand centers are considered as the three target areas to reduce CO_2 emissions during the distribution process. The research model was formulated as a mixed integer programming (MIP) problem. It achieves cost reduction, and will contribute to improvement of the natural environment.

Key words: Time-space network, Timetable, Transportation scheduling problem, Mixed integer programming (MIP) problem, Less-than carrier load
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1 Introduction

Currently, CO_2 emissions exacerbate global warming and other environmental problems. In Japan, the total CO_2 emissions in 2008 increased by more than 6% compared to that in 1990. The transport field accounts for 20% of the total amount of CO_2 emissions (National Greenhouse Gas Inventory Report of Japan, 2010). Therefore, modal shift, shifts of transportation carrier to lower-level CO_2 emission ones, such as from truck to freight railway or from airplane to container ship, can make significant contributions to the reduction of CO_2 emissions. Several traditional studies looked into the same model and explored the heuristics necessary for large-scale problems, but it was impossible for them to consider the timetable (Irohara and Kakumoto, 2009; Kakumoto and Irohara, 2010; Xue and Irohara, 2010). This study focuses on modeling of modal shift, taking into account not only transportation costs and CO_2 emissions, as traditional studies (Irohara and Kakumoto, 2009; Kakumoto and Irohara, 2010; Xue and Irohara, 2010) investigated, but also considering the time-space network problem to improve the modeling of the transportation problems. In order to solve this complicated problem, mixed integer programming (MIP) is used in this study, and the details were explained as follows.

1. Time-space network model. Time-space networks are used for emergency planning and location-based services. Kliewer *et al.* (2006) applied a time-space network model to a multi-depot bus scheduling problem considering a set of timetable trips. Yan and Shih (2007) developed a time-space

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network model to minimize the length of time needed for emergency repairs. George and Shekhar (2008) proposed a time-space network model called an aggregated graph, using less memory to find the shortest path with a fixed start time. However, there are only a few studies about transportation scheduling problems. Ohnishi (2007) used a time-space network model to solve an international transportation problem in consideration of the timetable. In this study, the time-space network model is used to solve the transportation problem with a timetable. Our problem consists of not only international but also domestic transportations.

2. Transportation problem with carrier choice. Transportation modes are becoming more complicated. For some companies, products are manufactured abroad, and then imported into the domestic market. During transportation, the companies confront the choice of transportation modes. Fujikawa *et al*. (2004) considered ship and airplane as transportation carriers. There is a trade-off relationship between the two carriers. A ship can transport more volume at less cost with less CO_2 emission than an airplane, but it consumes more time. Therefore, to find the optimal carriers is critical not only for cost consideration, but also for environmental improvement.

3. Less-than carrier load problem. Transportation of small-sized lots with high frequency can reduce the inventory, but it results in large CO_2 emissions. Okano *et al*. (2006) studied the less-than carrier load problem, which increases the utilization of each carrier's capacity by packaging different types of small-sized lots, reduces the transportation frequency, and as a result cuts CO_2 emissions. In this study, the methodology is incorporated to reduce CO_2 emissions.

4. Domestic transportation among demand centers. Ohnishi (2007) investigated not only direct transportation but also indirect transportation. For example, there are three centers, A (foreign), B (domestic), and C (domestic), and two orders, which require transportation from A to B and from A to C. Using only direct transportation, two international transportation carriers are needed: from A to B, and from A to C. Since international transportation costs more than domestic transportation, this method results in a higher cost. However, using indirect transportation, this request can be met with one international carrier and one domestic carrier. First, transport both orders from A to B (international), deliver one of the orders for B, and then transport from B to C (domestic) and deliver the rest orders for C. This method reduces the number of carriers, the total costs, and the CO_2 emissions.

2 Proposed model

2.1 Problem outline

In this study, a transportation scheduling problem is investigated, which is able to minimize not only the cost, but also the CO_2 emissions. Moreover, the time-space network enhances the feasibility of the model, making it possible to take into consideration the constraints of the timetables of each carrier and to allow connection amongst them. More specifically, this network considers whether or not a certain carrier is available at the location and in the time. It can be found out whether or not other carriers are able to be connected and to carry the order, if the first carrier is unavailable. The demand information, called 'order' in this study, is presented in an order table that provides information on demand quantities of the product, release dates, delivery due dates, and order destinations. Table 1 is an order table with 3 orders. For example, order 1 consists of 2 demand quantities of the product. It will be released on date 1, and must be delivered on date 4 in Tokyo. In this study, orders are transported from an overseas production base (Shanghai) to three demand centers in Japan (Tokyo, Osaka, and Kita-Kyushu). The objective of this model is to minimize both the transportation cost and the CO_2 emissions. The CO_2 emission volume is transformed into a CO_2 emission penalty expressed as a monetary value. The problem of minimizing the cost takes into account time constraints of the carriers. That is, the problem is based on a time-space network. This study focuses on three target areas to reduce CO_2 emissions in the distribution process. Firstly, the carrier choices must be carefully considered, since each carrier's transportation time, cost, and total CO_2 emissions differ. Secondly, less-than carrier load should be minimized. This study enables us to consolidate more than two orders and reduce the required number of carrier trips. Thirdly, this study enables connections between domestic transportation systems and international ones.

Table 1 Example of an order table

Order number	Demand quantity	Release date	Due date	Destination
1	2	1	4	Tokyo
2	20	2	6	Osaka
3	5	2	5	Kita-Kyushu

2.2 Time-space network

In a time-space network, a node has the information about both time and space, and an arc represents the movements of an order. Each order must follow a one-way path, shown as an arrow, and must reach its destination. Fig. 1 shows the time-space network constraints in this study, and how the orders are moved on the network can be established. For example, order 1 is released on date 1, and must be delivered on date 4 in Tokyo (Table 1). That is modeled as order 1 is to be sent from node (1, 1) and delivered to node (4, 2) in Fig. 1. For instance, if orders 2 and 3 can be sent together, first they are sent to Kita-Kyushu, and then order 2 is sent from Kita-Kyushu to Osaka. Therefore, in Fig. 1, the less-than carrier load problem is expressed as arrows moving from node (2, 1) to (5, 4), and finally to (6, 3). Compared to direct transportation, which means transporting orders from Shanghai to each destination directly, indirect transportation is more efficient and causes lower emissions of CO_2. This is because international transportation costs are higher than domestic ones.

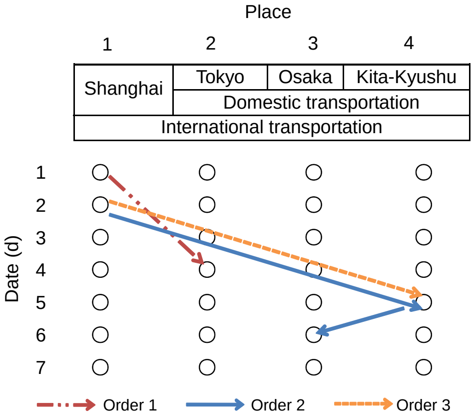

Fig. 1 Movements of the orders

Ships and airplanes are considered as international transportation carriers. Railways and trucks are used as domestic transportation carriers in this study.

As an example, Fig. 2 shows a time-space network for ships and railways (airplanes and trucks are omitted for simplicity), and the timetable of these four carriers is shown in Table 2. It is possible to use airplane and truck every day, ship on day 2, 5, 8, and railway only on odd days. Ships and railways emit much less CO_2 than that of airplanes and trucks. However, ships and railways are not available as much as we would like to because of the timetable constraint. Also, as shown in Fig. 2, the orders can only be transported on the arcs connecting two nodes, which represent the movements of the carriers.

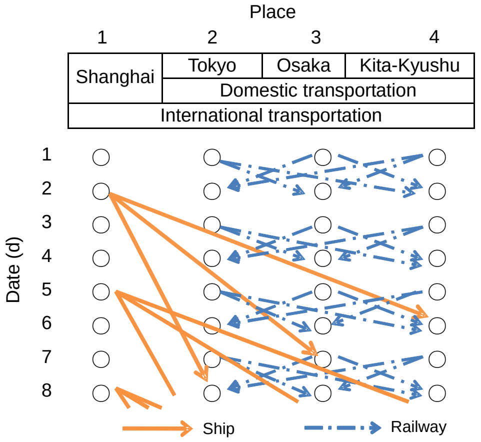

Fig. 2 Carriers used in the time-space network

Table 2 Timetable of each carrier

Carrier	Ship	Airplane	Railway	Truck
Day	2, 5, 8	Every day	Odd days	Every day

2.3 Formulation 1

The formulation for time-space network based transportation problem in this study is as follows.

$$\begin{aligned}\min Z = &\sum_m\sum_n\sum_s\sum_t\sum_p C_{mnstp} z_{mnstp} \\ &+\sum_i\sum_m\sum_n\sum_s\sum_t\sum_p E_{mnstp} D_i y_{imnstp},\end{aligned} \tag{1}$$

s.t.

$$\sum_i D_i y_{imnstp} \le M_p z_{mnstp},\ \forall m,n,s,t,p, \tag{2}$$

$$\sum_m\sum_n\sum_p y_{imnstp} - \sum_r\sum_w\sum_q y_{istrwq} = F_{ist},\ \forall i,s,t, \tag{3}$$

$$\sum_m\sum_s\sum_t\sum_p y_{im1stp} \ge 1,\ \forall i, \tag{4}$$

$$y_{imnstp} \le T_{mnstp},\ \forall i,m,n,s,t,p, \tag{5}$$

$$y_{imnstp} = \{0,1\},\ \forall i, m, n, s, t, p, \tag{6}$$

$$z_{mnstp} \ge 0,\ \forall m, n, s, t, p, \tag{7}$$

where i is the number of orders; (m, n), (s, t), (r, w) represent the node information as (time, place); p and q are indicative of carrier types (1, ship; 2, airplane; 3, railway; 4, truck); M_p is the maximum capacity of carrier p; D_i is the demand quantity of order i; C_{mnstp} is the cost of container of carrier p to transport from node (m, n) to node (s, t); E_{mnstp} is the CO_2 penalty cost of container of carrier p to transport from node (m, n) to node (s, t); z_{mnstp} is the number of container of carrier p needed to transport from node (m, n) to node (s, t); and

$$y_{imnstp} = \begin{cases} 1, & \text{order } i \text{ is transported by carrier } p \\ & \quad \text{from node } (m,n) \text{ to } (s,t), \\ 0, & \text{otherwise;} \end{cases}$$

$$F_{ist} = \begin{cases} 1, & s \text{ is the due date, and } t \text{ is the destination} \\ & \quad \text{for order } i, \\ -1, & \text{the order } i \text{ can be sent after date } s \text{ to city } t, \\ 0, & \text{otherwise;} \end{cases}$$

$$T_{mnstp} = \begin{cases} 1, & \text{carrier } p \text{ can go through node } (m,n) \text{ to } (s,t), \\ 0, & \text{otherwise.} \end{cases}$$

Eq. (1) is an objective function, which consists of transportation costs and CO_2 emission penalty costs. Eq. (2) expresses the constraints of the numbers of carriers. The total use of carriers must be no more than their total capacity. Eq. (3) constrains the transportation routes and the orders that must be transported to the destination node on the network. Eq. (4) means that at least one order is sent from Shanghai, and the order must be delivered to certain destinations. Eq. (5) represents timetable constraint. If T_{mnstp}=0, that means there is no carrier available for delivering from node (m, n) to node (s, t). That is, there is no route. Then in this case, y_{imnstp} must be zero. Eqs. (6) and (7) indicate the decision variables binary y and non-negative integer z.

Formulation 1 considers neither the capacity of the factory and the number of carriers nor the capacity of the distribution centers. To make the formulation more realistic, it is necessary to take into account the maximum flow of the distribution centers.

2.4 Formulation 2

Formulation 2 takes into consideration the maximum quantity Q that a distribution center can send every day.

$$\min Z, \tag{1}$$

s.t.

$$\text{Eqs. (2)–(7)},\quad \sum_i \sum_s \sum_t \sum_p D_i y_{im1stp} \le Q,\ \forall m. \tag{8}$$

3 Numerical experiments

In this study, the mathematical programming software CPLEX 10.1.0 is used to solve the MIP problem.

3.1 Experimental results of formulation 1

As shown in Table 3, results of the proposed model were compared with those of a traditional model that does not consider the time-space network (Irohara and Kakumoto, 2009). In the traditional study, ships and railways are available at anytime with no time constraints. However, in our proposed model E_2, the timetable of the carriers shown in Table 2 was used: ship departs every three days, railway departs every two days, and the others depart every day. Thus, with tighter and more realistic constraints, airplanes, and trucks are selected more often than ships and railways in E_2, resulting in both higher transportation costs and higher CO_2 emission costs.

Table 3 Experimental results of the models

Model	Number of containers				Cost (Yen)	
	Ship	Airplane	Railway	Truck	C_1	C_2
E_1	38	12	21	13	101 670	446
E_2	32	18	14	24	109 988	785

E_1: a traditional model with no time constraints (Irohara and Kakumoto, 2009); E_2: the proposed model with time constraints shown in Table 2. C_1: transportation cost; C_2: CO_2 emission penalty cost

The timetable of the carriers can be described in detail, with one day being divided into two parts: a.m. and p.m. (Table 4). Ship departs every third day in the morning, railway departs every other day at night, and the airplane and the truck depart in both the a.m. and the p.m. Results showed that taking time division into consideration, the costs increased (Table 5). Fig. 3 shows how time division impacts the execution time as the number of orders increases. It is found that the more divisions in one day, the more execution time is necessary to solve the problems.

Table 4 Detailed timetable of the carriers

Time	Ship	Airplane	Railway	Truck
a.m.	Every 3 d	○	×	○
p.m.	×	○	Every 2 d	○

○: available; ×: unavailable

Table 5 Experimental results of different time divisions

Model	Number of containers				Cost
	Ship	Airplane	Railway	Truck	(Yen)
E_2	32	18	9	19	110 773
E_3	28	22	14	21	119 838

E_2: a model with no time divisions; E_3: a model with one day divided into two parts

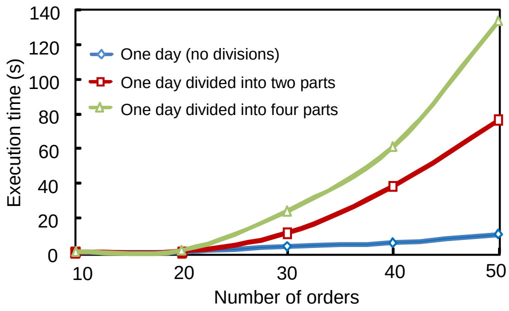

Fig. 3 Execution time of time divisions

As shown in Fig. 4, there is no constraint on the maximum quantity that a distribution center can manage. If the due dates are concentrated within several days in a month, a large number of orders are sent simultaneously on a certain day in order to save costs and reduce CO_2 emissions. However, this is unrealistic.

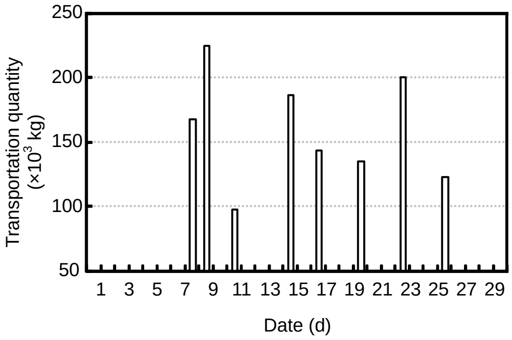

Fig. 4 Concentration of the release dates

3.2 Experimental results of formulation 2

According to Eq. (8), it is impossible to dispatch the orders greater than the maximum quantity which a distribution center can handle every day. Thus, the constraint of the orders dispatched from Shanghai is tighter than formulation 1.

Fig. 5 shows the experimental results compared to formulation 1 with the constraint of the maximum flow. When the due dates are concentrated within several days in a month, it costs less if the orders are sent together. However, this is impossible because of the limitation of the capacity of a distribution center. Therefore, compared to formulation 1, formulation 2 is more realistic in the case of the concentration of the due dates.

As shown in Fig. 6, the execution time of formulation 2 is longer because of the stricter constraint. Thus, if the due dates of the orders are not concentrated, formulation 1 can reach the optimal solution quicker. The execution time of the traditional model (Kakumoto and Irohara, 2010) is also shown in Fig. 6. Even for the small-scale problems, it takes longer to reach the optimal solution. And in the case of the order number being larger than 50, it cannot find the optimal solution.

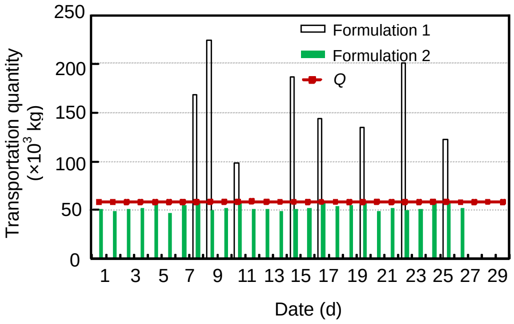

Fig. 5 Experimental results of formulation 2

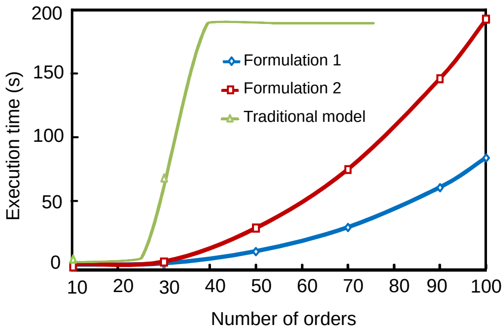

Fig. 6 Execution time of the formulations

4 Conclusions

This study focuses on modeling of modal shift, taking into account both transportation costs and CO_2 emissions. The objective is to minimize both transportation costs and CO_2 penalty costs. This study also considers the time-pace network problem, in order to manage the timetables of each carrier.

Thus, a time-space network is one of the most important parts in this study. With the time constraints of each carrier, a more detailed schedule of the orders is considered. In addition, compared to the traditional method, the model proposed in this study can also deal with large-scale problems, and can obtain the optimal solution in a shorter time. Experimental results prove the efficiency of the time-space network constructed in this study.

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