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Freight transportation planning in platform service supply chain considering carbon emissions

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ABSTRACT

The online-to-offline (O2O) platform is becoming increasingly popular in today's market. This study investigates the decision-making problem of an O2O freight platform facing uncertain demand and carbon emission constraints to achieve sustainable development and establish an environment-friendly image. By receiving customer orders online and then delivering them offline, the platform chooses the optimal dispatching time and pricing level to maximize its profit under a limited carbon cap. We consider a stochastic model with two kinds of demand functions, i.e., additive and multiplicative cases, and solve the optimization problems. By adopting a data set from a leading O2O freight platform in China, we find that the proposed model can effectively increase the revenue of the platform by more than 20 % if the platform increases the price appropriately. The results further show that market parameters such as potential market size and price elasticity have a more significant influence on the price decision than logistics parameters such as the fixed shipping cost and holding cost per unit volume per unit time, while logistics parameters affect the dispatching time decision more significantly than market parameters. With respect to the profit, as the carbon cap increases, the profit of the platform first climbs up to a peak point and then decreases with the further increase of the cap due to rising inventory holding costs. Furthermore, the O2O platform can benefit from a large-scale market and thus might suffer a loss at its start-up stage. Our study contributes to the literature on the O2O platform and the freight transportation planning with the consideration of sustainable development.

1. Introduction

The service industry contributes more to the world economy than any other industry today. It is reported that over 90 percent of the American GDP is produced by the service industry (Wang et al., 2015), and this proportion has also exceeded 50 percent in China, presenting an upward trend. In the service supply chain (SSC), the matching between the demand and the supply is critical for the whole supply chain to achieve sustainable development. Companies take various measures to optimally allocate the supply to the demand side. For example, in online-to-offline (O2O) service platforms, the introduction of outsourcing capacity can effectively improve the on-time rate of orders and thus increase the total revenue of the platform (Dai et al., 2017). In addition, companies are making efforts to reduce carbon emissions to align with government regulations on green development. For example, Siemens purchases a lot of energy-efficient equipment to reduce carbon emission, such as motors and pumps. Moreover, the amount of carbon emission can be effectively reduced by optimizing the operational process of companies.

According to the Industry Information Network of China, the market size and the freight volume of the intra-city freight industry in 2019 have reached 1.3 trillion yuan and 20.3 trillion tons, with a year-on-year increase of 7.8 % and 3.57 %, respectively. As for the market share, the business-side and consumer-side services account for 97 % and 3 % of the market, respectively. In intra-city goods transportation, the general shipping distance ranges from a few kilometers to tens of kilometers. Usually, the order charge is related to the time urgency and the shipping distance of the order. For example, in China, logistics companies such as Dada Express normally charge more than 10 yuan per order if the shipping distance is within 2 km and the weight is within 5 kg and promise to deliver it within 1 h per 3 km, while other companies such as Zhuanxianbao promise to deliver orders within the same city on the

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same day with much lower charges. In traditional freight industry, due to information asymmetry, the efficient match between freighters and drivers is hard to achieve (Li et al., 2020) and route planning problems need to be considered to save shipping costs. For O2O freight platforms that gather information from both the third-party trucks and freighters, effective supply-demand matching (car-to-cargo matching) can be achieved without considering route planning problems.

Moreover, O2O freight platforms usually face uncertain demand and the carbon emission constraint from the government. On the one hand, the potential demand is usually related to the price charged by the platform, and the demand uncertainty makes it hard to decide on the charged price. On the other hand, the inventory holding costs occur if the goods are not dispatched immediately, while frequent dispatch will inevitably lead to increased transportation costs. Thus the pricing and dispatching time decisions are the two most important choices of those companies. Since there are carbon caps for the companies, they should make choices within an upper limit on the amount of carbon emission. Further, reducing carbon emission can benefit companies in several ways, such as increasing consumer favorability, obtaining more brand attraction, and enhancing the intrinsic value of the company by attracting more investors and realizing the sustainable development.

This study focuses on freight transportation planning in the platform service supply chain (PSSC). We aim to provide the optimal freight transportation planning for an O2O freight platform facing uncertain demand and the carbon emission constraint. The O2O freight platform, we hereafter refer to company Y, receives customer orders online and then deliver those orders offline. We assume the delivered goods (here, we only consider the volume of the goods rather than the shape and size) will be first gathered in the warehouse of company Y once the order is placed online, and then dispatched to their destinations. Since the market is an international commodity trading center, such as Yiwu International Trade City, Huaqiangbei Electronics Market in Shenzhen, the location of the warehouse is very close to the market, and all the orders come from the market, we hardly need to spend much time and cost to deliver the goods to the warehouse once an order is placed. Therefore, the time and cost in the gathering process are not needed to be considered. Company Y decides the prices charged to customers and the time intervals that trucks of company Y depart from the warehouse to deliver the goods. To the best of our knowledge, this study might be the first in literature to address the decision-making problem of an O2O platform with uncertain demand and the carbon emissions constraint.

In practice, most O2O platforms rely on past experience to make decisions. However, it is often difficult to achieve ideal results (Aydogan, 2021). To gain the maximal profit, we propose a stochastic model with the carbon emission constraints, where two demand structures are applied, i.e. additive and multiplicative cases. We then provide a new method to optimize the price and the time interval of departure with the carbon emission constraint, which has not been studied in literature yet. Further, by applying real-life data from a big O2O freight platform, we conclude that the price decision is more sensitive to market parameters (i.e. market size, price elasticity) than to logistics parameters (i.e. fixed shipping cost, holding cost), and logistics parameters have a more significant impact on time decisions than market parameters. Further, the profit will rise up to a peak point with the increase of the environment parameters (i.e. carbon cap) and then the profit will decrease. To the best of our knowledge, this study is the first in literature to address the decision-making problem facing by an O2O platform with uncertain demand and the carbon emissions constraint.

The remainder of this paper is organized as follows. In section 2, a comprehensive literature review on the SSC management and freight transportation planning is presented. Problem description and model formulation are provided in section 3. Section 4 presents model analysis and numerical study is illustrated in section 5. Finally, the conclusion and future research are given in section 6.

2. Literature review

This study is closely related to three streams of literature: sustainable logistics supply chain management, freight transportation planning, and carbon emission in the supply chain.

2.1. Sustainable logistics supply chain management

The optimization problem of supply chain management has been widely explored in literature, and many studies have been published in this field (e.g., Wang et al., 2015; Ma and Zhang, 2009; Van den Broeke et al., 2015). Specifically, sustainable logistics supply chain management has been comprehensively explored by Tseng et al. (2018), Schliwa et al. (2015), and Liu et al. (2018).

In the field of sustainable logistics supply chain management, many researchers concentrate on environmental crises. Das and Jharkharia (2019) study the sustainable logistics issues in the supply chain. They establish a variance-based structural equation modeling technique to examine the relationship between low carbon supply chain practices and their relationship with environmental sustainability (ES) and the economic performances (EP) of Indian manufacturing firms. By analyzing the operating data of 83 Indian manufacturing firms, they find that low carbon purchasing is positively related to the adoption of low carbon product and process design, while there is no significant relationship between low carbon supply chain practices and the EP of a firm. Hong et al. (2019) present a mathematical programming model to improve the release of particulate pollution (PM2.5) into the atmosphere by minimizing the transportation costs and the social medical costs. By examining the total cost and the release of PM2.5 from testing different modes of transportation, they show that the decision makers can reduce the total costs and protect the environment by selecting the most suitable transportation method. Further, some emerging technologies are used in supply chain management to achieve sustainable development. Esmaeilian et al. (2020) provide a framework of Blockchain technology and Industry 4.0 towards sustainable development in the supply chain management. First, the sustainability of Industry 4.0 has been evaluated in three topics, such as the Internet of things (IoT)-enabled energy management in smart factories, smart logistics and transportation, and smart business models. By applying Blockchain technology on the basis of Industry 4.0, they show that blockchain technology has a positive performance in reducing operating costs, enhancing product life cycle visibility, and detecting the healthy development of supply chain networks. Lesueur et al. (2020) provide a forward-looking viewpoint on the use of blockchain technology for logistics and supply chain management, and indicate that blockchain technology can be comprehensively applied in inventory management, smart contract design, information transparency, etc.

2.2. Freight transportation planning

Freight transportation planning is an indivisible part of supply chain sustainability. Well-organized planning can significantly cut costs and thus increase profitability. We further discuss previous literature on *Logistics network* and *Freight transportation planning.*

Logistics network have gradually been regarded as a new trend in recent decades. Van Duin (1970) surveys sustainable urban freight policies in the Netherlands, and then explores the possible roles of the platforms and companies played in sustainable freight policies. Lindholm and Blinge (2014) evaluate the knowledge and awareness on sustainable urban freight transportation of local policymakers in Sweden. Their empirical study reveals the existing drawbacks and four insightful suggestions for policymakers. In terms of the logistics network, Lee et al. (2010) study the design of a sustainable logistics network and develop an improved sample average approximation approach based on a network in the Asia Pacific region, which is proved to be efficient. Taskhiri et al. (2016) focus on the renewable resource of wood in a sustainable logistics network. They propose a mixed-integer linear programming (MILP) model by considering the wood flow in different sectors and show that it can significantly reduce carbon emission.

For Freight transportation planning, SteadieSeifi et al. (2014) review the literature on multi-modal freight transportation planning from 2005 to 2014 and then propose an agenda for future research. Dube et al. (2014) study the multimodal freight transportation planning considering several factors, e.g., capacity constraints, carriers schedules. They present several analytic tools to improve the efficiency of the purchase procedure, carrier selection, and business rule management. Baykasouglu and Subulan (2016) formulate a multi-objective mix-integer model to minimize the sum of transport cost, transit time, and carbon emission. Borndorfer et al. (2016) study the freight train routes scheduling with passengers and freight trains. Mixed-integer nonlinear programming (MINLP) is formulated to minimize the total cost of expected delays and traveling time, and the effectiveness of the model is tested by various real-world examples. While some research focuses on solving algorithms for this problem, Li and Li (2018) study the order allocation and route optimization problem in an O2O platform. With the objective of minimizing the distribution cost, a mixed integer planning model is established and a genetic algorithm is developed to solve the problem. The results show that the total distribution cost can be reduced by increasing the estimated delivery time. Zhu et al. (2017) consider simultaneous delivery and pickup in the freight delivery problem and design a multiple neighborhood guided local search algorithm to solve this NP-Hard problem. By comparing with other approaches in previous studies, the experimental results show that this algorithm can yield a better solution in terms of performance and stability, but it does not have an advantage in terms of solution time.

2.3. *Carbon emission in the supply chain*

Carbon emission has played an increasingly important role in the sustainable development of the supply chain. In the following part, we will review *carbon emission in operation management* and *the measures to reduce carbon emission*.

Li et al. (2018) aim to minimize the sum of vehicle fixed cost, carbon emission, and fuel consumption, by designing a split-based adaptive tabu search (SATS) algorithm to solve this vehicle routing problem. The numerical experiments verify the effectiveness of the algorithm. Daryanto et al. (2019) propose an integrated three-echelon supply chain model, which considers the carbon emission and disposing of the deteriorated items. They aim to minimize the sum of the buyer's cost and emission, the logistics service provider's cost and emission, and the supplier's cost and emission by optimizing the number of deliveries per cycle. Bai et al. (2019) investigate the carbon emission from the management of deteriorating products under vendor-managed inventory. Then a revenue-sharing contract is proposed to improve the total profit and carbon emission. Their results show that the system can be coordinated perfectly when the demand depends on the manufacturer's green technology level and two competing retailers' selling prices.

Yu and He (2019) apply the idea of graph theory to the design of low-carbon products, optimize the low-carbon design method of products based on graph theory, and integrate the idea of "break up the whole into parts" into the design of each raw material to minimize the carbon footprint. This solves the problem of inaccurate carbon footprint calculation in previous methods. Waheed et al. (2019) study the relationship between economic growth, energy consumption, and carbon emission. They find that in developed countries, economic growth has nothing to do with carbon emission, while in developing countries, greater energy consumption can lead to a higher economic growth. In both developed and developing countries, greater energy consumption will lead to a higher carbon emission, and relevant suggestions have been given to reduce carbon emission. From the perspective of energy conservation and emission reduction, Cai et al. (2019) establish a state space model of the carbon footprint in terms of energy consumption and waste emissions, which consists of four steps: clarifying the current situation, analyzing the root cause, improvement, evaluation of the carbon emissions, sustaining and standardizing, and then applying the model to Zcrubber Group Co. Ltd.

In order to achieve the sustainable development of the platform, some researchers study the PSSC (Li and Li, 2018; Zhu et al., 2017; Gu and Huang, 2018; Jiang, 2018; Vancza et al., 2010; Dai et al., 2019), but those works mainly consider vehicle routing problem (VRP) or consumer behavior. Recently, Shen et al. (2019) apply data mining with social media data and study the future development trend of O2O platforms. Choi and Choi (2019) and Pei et al. (2019) study the development of O2O platforms from the perspective of user behavior. In addition, Wang et al. (2019a, 2019b) study the impact of policies and regulations on the competition in the bilateral taxi market. Specifically, some researchers have studied the freight transportation planning in the PSSC. For example, Ursavas and Zhu (2018) investigate the freight transportation planning problem in a rail network with dedicated tracks and shared-use corridors. They analyze different characteristics of passenger and freight trains and explore the best track distribution plan of the railway station to obtain the optimal transportation price and delivery time interval. Based on the Dutch railway system, their approaches can efficiently increase the profit of the railway station. However, they do not consider the capacity of the vehicles in every shipment or other constraints such as environment factors (i.e. carbon emission). Dube et al. (2014) study the problem with capacity constraints and deterministic demand. Li et al. (2020) establish a mixed integer programming model to address the freight transportation problem, but they mainly focus on price decision in different situations. However, we have not found studies that explore the sustainable development of the platform by considering both the price strategy of O2O platforms and carbon emissions. Manupati et al. (2019) study the capacity allocation and inventory in multi-echelon supply chain with three policies (carbon tax, strict carbon cap, and carbon cap-and-trade) and lead time consideration, but the price factor is not considered in the model. Liu et al. (2020) study a joint distribution-green vehicle routing problem with the objective of minimizing the total cost with the carbon emission consideration.

Previous literature mainly studies the optimization problems in logistics and supply chains with deterministic demand. Few studies consider the platform-based service supply chain with stochastic demand, especially by combining the sustainable development of the O2O platform with a green economy. In this paper, we study the pricing decision and delivery time decision of a O2O freight platform with stochastic demand and the consideration of carbon emissions to achieve the sustainable development of the platform. The detailed comparison is shown in Table 1.

3. Problem description and model formulation

We consider an O2O freight platform (i.e., company Y). Company Y is one of the largest O2O freight platforms in Wuhan, China, in terms of average daily order volume and the number of wholesalers and small

Table 1
Comparison between literature and this study.

Authors	Price	Time	Route	Constraint	Carbon emission	Problem Type	Solution Methodology
Lee et al. (2010)				✓		Stochastic	Stochastic optimization
Li and Li (2018)			✓	✓		Deterministic	Genetic algorithm
Zhu et al. (2017)			✓	✓		Deterministic	Heuristic algorithm
Taskhiri et al. (2016)				✓		Deterministic	MILP
Baykasouglu and Subulan (2016)		✓		✓	✓	Deterministic	Fuzzy goal programming approach
Dube et al. (2014)		✓	✓	✓		Deterministic	Data Analysis
Ursavas and Zhu (2018)	✓	✓				Stochastic	Stochastic programming
Li et al. (2020)	✓		✓	✓		Deterministic	Heuristic algorithm
Li et al. (2018)	✓		✓	✓	✓	Deterministic	Tabu search
Daryanto et al. (2019)	✓			✓	✓	Stochastic	Stochastic programming
Bai et al. (2019)	✓			✓	✓	Stochastic	Stochastic optimization
This paper	✓	✓		✓	✓	Stochastic	Stochastic programming

retailers. By applying big data technology, company Y can quickly match available trucks with customer orders. Typically, the customers submit their order information by using the mobile application of company Y, including the departure address, the delivery destination, the type and the volume of the goods, etc.

Company Y receives customer orders online and then deliver the goods offline to customers. Once a customer order is placed, the goods of the customer will be gathered in the warehouse of company Y, which is located in the central position of the freight market. Company Y needs to decide the price charged to consumers based on the volume of the goods. The potential demand is related to the price charged by company Y. After a certain period of time, all goods stocked in the warehouse will be dispatched to their destinations. During the transportation, the carbon emission is generated due to the fuel consumption, excessive carbon emission will not only affect the brand effect of platform, but also inevitably influence the sustainable development of the platform. Once the goods arrive at the warehouse and are not dispatched immediately, the holding cost occurs. The amount of the holding cost is determined by the volume of the stocked goods and the length of the storage time, and thus dispatching on time can efficiently reduce the holding cost. However, frequent dispatch will inevitably lead to increased transportation cost and carbon emission.

To focus on our primary purpose, we have the following assumptions. First, there is only one company that provides freight transportation services in the market. Second, we consider a setting from a real case that the market is an international commodity trading center and the location of the warehouse is right in the market. Since all the orders come from the market, the goods are easily stored in the warehouse once an order is placed. Thus, in our model we ignore the time and the cost in the gathering process and concentrate on the pricing and dispatching decisions. Third, the gathered goods will be first dispatched to a delivery point, and then delivered to each of their destinations. Because the destinations of the O2O freight platform for transporting goods are very concentrated, we assume that all destinations are in the same place and we do not consider the last mile delivery in our model. We assume company Y will charge a price P and determine the cycle length T, where P denotes the price per unit volume for the total distance to be traveled. In this context, we aim to maximize the profit by determining the optimal price P and the optimal cycle length T under the carbon cap.

The objective function of this problem consists of two parts, including the revenue and the cost. Renewal reward theory can be applied to compute the expected profit $\pi(T, P)$, which is given by

$$\pi(T,P)=\frac{\mathbb{E}(\text{revenue incurred during a cycle})-\mathbb{E}(\text{costs incurred during a cycle})}{T}. \tag{1}$$

A plausible assumption is that the arrival process of orders is presented by a compound Poisson process, then we can obtain

$$Y(t)=\sum_{n=1}^{N(t)}V_n,$$

where $Y(t)$ is the total volume of orders arrived at time t, $N(t)$ is the number of arrived orders at time t, and V_n is the volume of the nth order. We further assume that λ denotes the arrival rate of orders and the mean of V_n is given by μ_V. Another reasonable assumption is that $N(t)$ is independent of V_n, which means the arrival time of orders is not related to the volume of orders. The total volume of orders is denoted by $\sum_{n=1}^{N(T)}V_n$. The revenue depends on the price and total volume of orders, and then the expected revenue per cycle can be described as multiplying the price by the demand, that is

$$\mathbb{E}(\text{revenue incurred during a cycle})=P\mathbb{E}(V_n)\mathbb{E}(N(T)). \tag{2}$$

Where $\mathbb{E}(V_n)$ is the expected volume of V_n and $\mathbb{E}(N(T))$ denotes the expected number of orders in cycle length T.

The total cost can be partitioned into the transportation costs and the holding costs during a cycle, thus

$$\begin{aligned}\mathbb{E}(\text{total costs during a cycle}) &= \mathbb{E}(\text{transportation costs during a cycle})\\ &\quad+\mathbb{E}(\text{holding costs during a cycle}).\end{aligned} \tag{3}$$

We first present the expected transportation costs, which contains a fixed fee and a variable cost. The fixed cost contains the sum of the fuel cost, personnel cost, and set-up cost while the variable cost depends on the volume of orders and the travel distance. Overall, the total transportation costs can be expressed as

$$\mathbb{E}(\text{transportation costs during a cycle})=K+d\beta\times\mathbb{E}(V_n)\mathbb{E}(N(T)), \tag{4}$$

where K is the fixed cost, β is the variable cost, and d is the number of kilometers to be traveled.

The holding cost depends on the volume of customer orders and the storage time before the goods are dispatched. The arrival process of customer orders is illustrated in Fig. 1. The length of the storage time within one cycle is given by T. S_i and V_i denote the arrival time and the volume of the ith order, respectively. T_i means the time interval between $(i-1)$th and ith order, and we assume that the interval time of the first

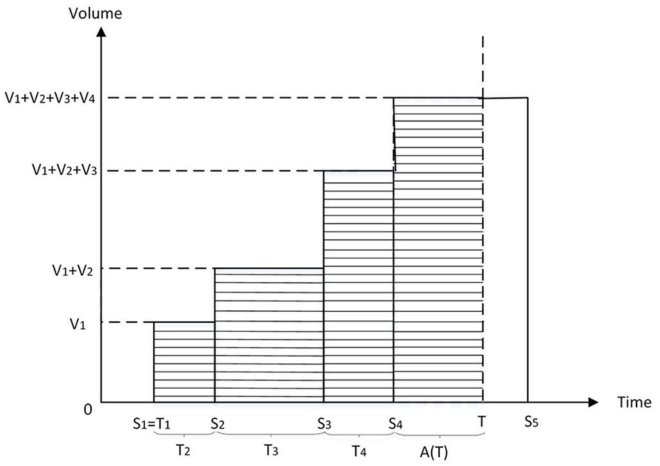

Fig. 1. Arrival process of orders (Ursavas and Zhu, 2018).

order is equal to its arrival time, i.e. $T_1 = S_1$. Between the time interval S_2 and S_3 (i.e., T_3), the total volume to be dispatched is $(V_1 + V_2)$ (the shaded part in Fig. 1). The time interval between the last arrival and T is defined as $A(T) = T - S_{N(T)}$, where $N(T) = 4$ in Fig. 1.

Then the holding costs during a cycle can be defined as

$$\mathbb{E}(\text{holding costs during a cycle}) = \mathbb{E}\left(h \times \left(\sum_{i=2}^{N(T)} T_i \sum_{j=1}^{i-1} V_j + A(T) \sum_{i=1}^{N(T)} V_i\right)\right), \tag{5}$$

where h is the holding cost per unit volume per unit time.

Actually, the volume in each order is not necessarily the same. From Fig. 1, we can find that the volume of each order can be different. Here, we denote μ_v as the average volume per order. By applying the properties of the compound Poisson process, we can obtain

$$\begin{aligned} \mathbb{E}\left[\sum_{i=2}^{N(T)} T_i \sum_{j=1}^{i-1} V_j\right] &= \mu_v \mathbb{E}\left[\left(\sum_{i=1}^{n-1} i\mathbb{E}[T_{i+1}|N(T) = n]\right)\right] \\ &= \frac{\mu_v}{2\lambda}(\lambda^2 T^2 - 2\lambda T - 2e^{-\lambda T} + 2), \end{aligned}$$

and $\mathbb{E}A(T) = (1 - e^{-\lambda T})/\lambda$.

Substituting the above expressions into (5), we can obtain the holding costs as $h\mu_v \lambda T^2$. Finally, the simplified expression of the optimization problem can be written as

$$\underset{T>0,\ P>0}{\text{maximize}}\ \pi(T,P) = \frac{1}{T}\left(P\mathbb{E}(V_n)\mathbb{E}(N(T)) - K - d\beta \times \mathbb{E}(V_n)\mathbb{E}(N(T)) - \frac{h\mu_v \lambda T^2}{2}\right) \tag{6}$$

s.t.

$$s_0 \mathbb{E}(V_n)\mathbb{E}(N(T)) \le C. \tag{7}$$

where constraint (7) indicates that the amount of carbon emissions cannot exceed a certain cap C and s_0 denotes the amount of carbon emission per unit volume per unit time and the unit is kg $CO_2/(hour \cdot m^3)$.

From (6) and (7), it is clear that carbon caps can significantly influence the optimal cycle length T. Specifically, when the carbon cap is at a low level, it requires the cycle length to be as short as possible. Further, T is related to the price P. Therefore, an appropriate carbon cap contributes to the profit of the platform.

Since the transportation service is outsourced to a third-party logistics provider, the platform has to pay the transportation costs defined by (4). Thus, our model does not consider the issues related to the number of trucks and the corresponding truck capacity.

Demand uncertainty has also a significant impact on price decisions and delivery cycle in the service supply chain management (Modak and Kelle, 2019). In this paper, we have established a model with the carbon emission constraint under uncertain demand. Due to the characteristics of the market, the demand is relatively strong during holidays while the demand is relatively flat for other times, which causes a cyclical change in orders. In addition, different demand types need different services. For example, customers with urgent needs are usually not sensitive to the price charged by the O2O platform but pay more attention to the impact of delivery time, while other customers may not be sensitive to the time but prefer a low price. Therefore, the pricing and delivery time decisions are imperative for the O2O platform.

4. Model analysis

In this section, we consider two types of demand models, i.e. additive and multiplicative, to characterize the relationship between the demand and the price. The additive model assumes that the demand has a linear relationship with the price and the multiplicative model has a curvilinear relationship (Tellis, 1988).

4.1. Additive model

We assume that the average demand rate is given by $\lambda = a - bP$, where a is the potential market size and b is the price elasticity of demand. Then the optimization problem can be expressed as

$$\underset{T>0,\ P>0}{\text{maximize}}\ \pi(T,P) \quad = \quad (P - d\beta) \times \mu_v(a - bP) - \frac{K}{T} - \frac{h\mu_v(a - bP)}{2}T \tag{8}$$

s.t.

$$s_0\mu_v(a - bP)T \le C, \tag{9}$$

where the constraint (9) indicates that the amount of the carbon emissions in a cycle should be no more than the carbon cap C.

Lemma 4.1. *For a given P, the optimal cycle length T* is given by*

$$T^*(P) = \begin{cases} \sqrt{\dfrac{2\ K}{h\mu_v\lambda}}, & \text{if } \sqrt{\dfrac{2\ K}{h\mu_v\lambda}} \le \dfrac{C}{s_0\mu_v\lambda}; \\ \dfrac{C}{s_0\mu_v\lambda}, & \text{Otherwise.} \end{cases} \tag{10}$$

Based on Lemma 4.1, the global optimal solution can be characterized by the following theorem.

Theorem 4.2. *There exists a value $P_0 \in [0,\ P_u]$ that satisfies the first derivative of $\pi(T,\ P)$ equals to 0, then we have*

1) *If $\sqrt{\frac{2\ K}{h\mu_v\lambda}} \le \frac{C}{s_0\mu_v\lambda}$, i.e. $P \in S_1$, and S_1 denotes the set $[P_l, P_u]$, $P_l = \frac{a}{b} - \frac{hC^2}{2bK\mu_v s_0^2}$, $P_u = \frac{a}{b}$, the optimal solution is given by*

$$(T^*(P^*), P^*) = \begin{cases} P^* = P_0, \mathit{and}\ T^*(P^*)\ \mathit{can\ be\ found\ from}(10), & \text{if } P_0 \in S_1; \\ P^* = P_l, \mathit{and}\ T^*(P^*)\ \mathit{can\ be\ found\ from}(10), & \text{if } P_0 < P_l; \end{cases} \tag{11}$$

2) *If* $\sqrt{\frac{2\ K}{h\mu_v\lambda}} > \frac{C}{s_0\mu_v\lambda}$*, i.e.* $P \in S_2$*, and* S_2 *denotes the set* $(0, P_l), P_l = \frac{a}{b} - \frac{hC^2}{2bK\mu_v s_0^2}$*, the optimal solution is given by*

$$(T^*(P^*), P^*) = \begin{cases} P^* = P_0, \textit{and } T^*(P^*) \textit{ can be found from } (10), & \text{if } P_0 \in S_2; \\ P^* = P_l, \textit{and } T^*(P^*) \textit{ can be found from } (10), & \text{if } P_0 > P_l. \end{cases} \tag{12}$$

4.2. Multiplicative model

For the multiplicative model, we assume that the average demand rate is given by $\lambda = aP^{-b}$, where a and b are the coefficients of the function, and $a > 0$, $b > 0$. Then the optimization problem (6) can be rewritten as

$$\underset{T>0,\ P>0}{\text{maximize}}\ \pi(T, P) \quad = \quad (P - d\beta) \times \mu_v a P^{-b} - \frac{K}{T} - \frac{h\mu_v a P^{-b}}{2} T \tag{13}$$

s.t.

$$s_0 \mu_v a P^{-b} T \leq C, \tag{14}$$

For any given P, we can show that the profit function $\pi(T, P)$ is strictly concave in T, and the optimal $T^*(P)$ is also given by Lemma 4.1, which can be proved by a similar method. Then we can obtain the optimal solution by Theorem 4.3.

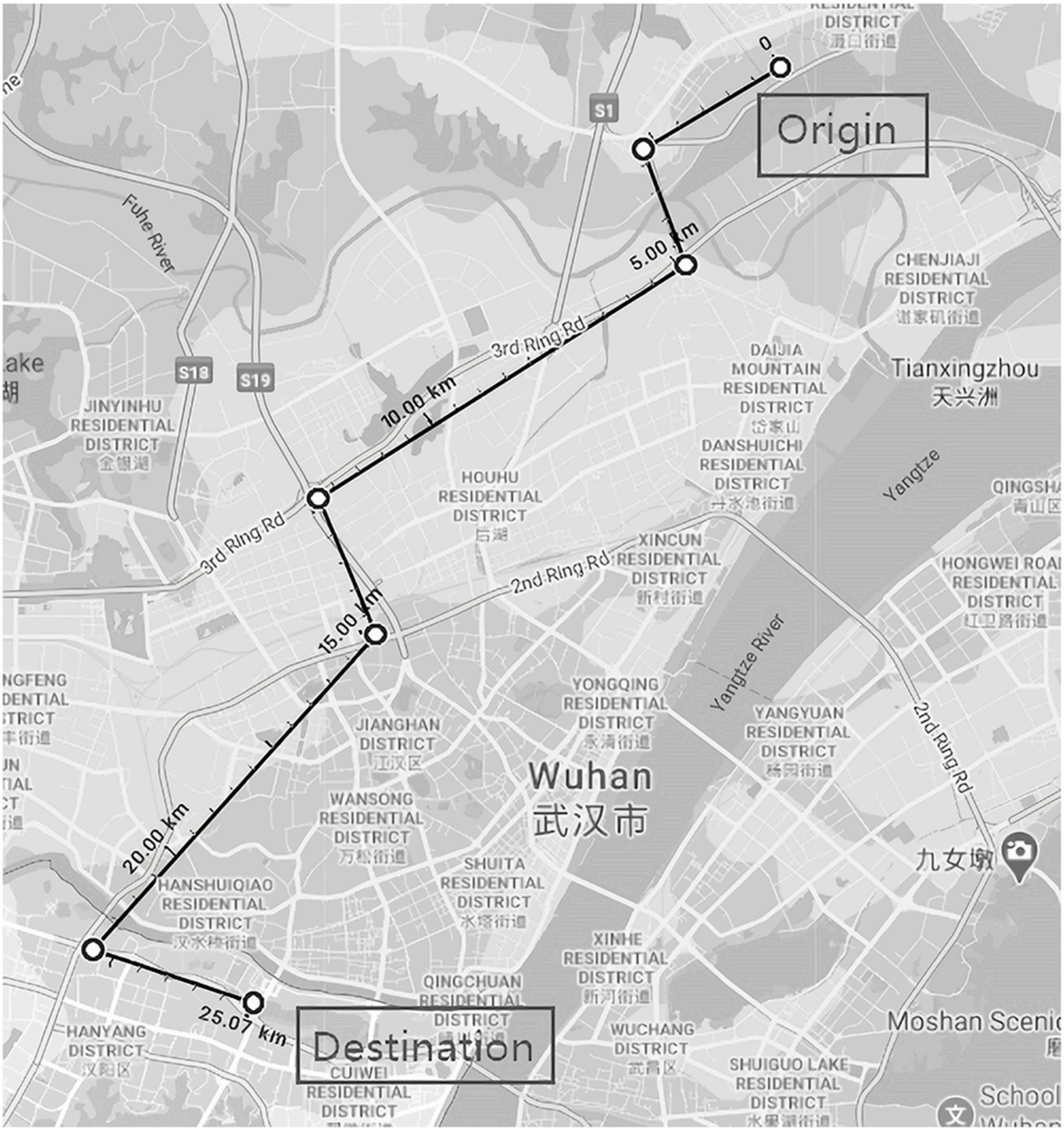

Fig. 2. The route from company Y to location A (source: Google Map).

Theorem 4.3. *There exists a value $P_0 \in (0, P_u]$ that satisfies the first derivative of $\pi(T, P)$ equal to 0, where P_u is the upper bound of the price, then we can obtain the optimal solution as follows.*

1) *If $\sqrt{\frac{2\ K}{h\mu_v\lambda}} \le \frac{C}{s_0\mu_v\lambda}$, i.e. $P \in S_1$, and S_1 denotes the set $[P_l, P_u], P_l = (\frac{2aK\mu_v s_0^2}{hC^2})^{\frac{1}{b}}$, the unique optimal solution is given by the three cases:*
   - (i) *For $b < 2$, the optimal solution $(T^*(P^*), P^*)$ is given by*

$$(T^*(P^*), P^*) = \begin{cases} P^* = P_0, and\, T^*(P^*)\, can\, be\, found\, from (10), & \text{if } P_0 \in S_1; \\ P^* = P_l, and\, T^*(P^*)\, can\, be\, found\, from (10), & \text{if } P_0 < P_l. \end{cases} \quad (15)$$

   - (ii) *For $b = 2$, the optimal solution $(T^*(P^*), P^*)$ is given as follows. if $\triangle - 1 \le 0$, then the optimal solution is $(T^*(P_l), P_l)$; otherwise, the optimal solution is $(T^*(P_u), P_u)$.*
   - (iii) *For $b > 2$, if*

$$d\beta b - (b-1)P + \triangle P^{\frac{b}{2}} \ge 0,$$

where $\triangle = b\sqrt{\frac{Kh}{2a\mu_v}}$, then the optimal solution is $(T^*(P_u), P_u)$; otherwise, the optimal solution is $(T^*(P_l), P_l)$.

2) *If $\sqrt{\frac{2\ K}{h\mu_v\lambda}} > \frac{C}{s_0\mu_v\lambda}$, i.e. $P \in S_2$, and S_2 denotes the set $(0, P_l), P_l = (\frac{2aK\mu_v s_0^2}{hC^2})^{\frac{1}{b}}$, the optimal solution is given by the two cases:*
   - (i) *For $b \le 1$, the unique optimal solution is given by $(P_l, T^*(P_l))$.*
   - (ii) *For $b > 1$, there exists a value $\overline{P} = \frac{b\beta dC + bKs_0}{C(b-1)}$ satisfying*

$$d\beta b - (b-1)p + \frac{bKs_0}{C} = 0,$$

If $P_l \le \overline{P}$, the unique optimal solution is given by $(T^*(P_l), P_l)$; otherwise, the optimal solution is given by $(T^*(\overline{P}), \overline{P})$.

5. Numerical study

In this section, we use a real data-set from company Y to illustrate the problem. Company Y mainly provides intra-city delivery service for individual wholesalers. Company Y first gathers the items of customer orders in its own warehouse, and then dispatches them to their destinations by trucks. From Fig. 2, the route from the warehouse of company Y (origin) to location A (destination) is the main service route of company Y, where orders to location A account for one-third of the total order volume, and other orders are distributed to more than a dozen other destinations. Thus we adopt the real data of this route to test our model.

The total distance from the warehouse of company Y to location A is 25 km, where the *Origin rectangle block* denotes the location of the warehouse and *destination rectangle block* means the destination of orders. Since the destinations of the orders are significantly concentrated, then we assume that all the delivery locations are in the same place (i.e. only one destination). To achieve sustainable development, the platform has to make restriction on the amount of carbon emissions caused by transportation. To maximize the profit, the price P and the cycle length T need to be decided under the carbon cap.

All experiments in this section are programmed in python language version 3.7.6 and run on a personal computers with a 64-bit Windows system with Intel Core (i7-9700 CPU, 3.0 GHz). The results can be obtained within 1 s.

5.1. Data analysis and results

The order data represents the number of orders received by company Y between July 1st and July 15th in 2019. During this time period, a total of 1952 orders with a mean of 130.13 and a standard deviation of 10.04 are generated. Based on the statistical analysis, we can obtain that the number of arrival orders follows a Poisson distribution with an average rate of 16.39 per hour, which shows the potential market size.

The delivered goods of company Y are mainly textiles, clothing, shoes, toys, etc. We set $b = 0.055$, the average order volume $\mu_v = 0.05$ m^3, holding cost $h = 0.2$ RMB per unit volume per unit time, and the carbon cap $C = 1000g$. Currently, the platform chooses the dispatched trucks cycle length $T = 3$ h and $P = 200$RMB/m^3. The profit is 120 RMB per unit time.

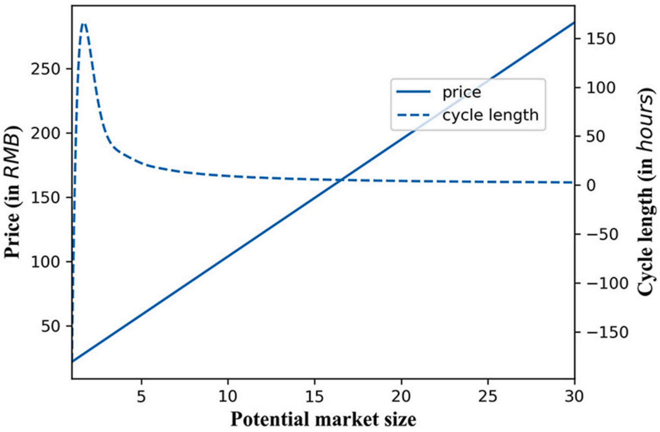

Fig. 3. The impact of the potential market size on the optimal solutions.

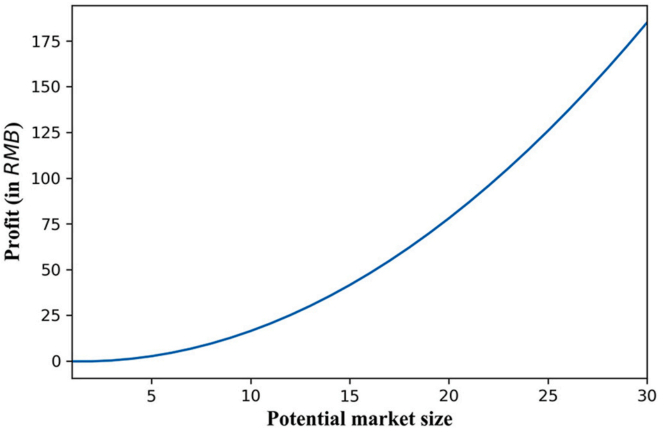

Fig. 4. The impact of the potential market size on the profit.

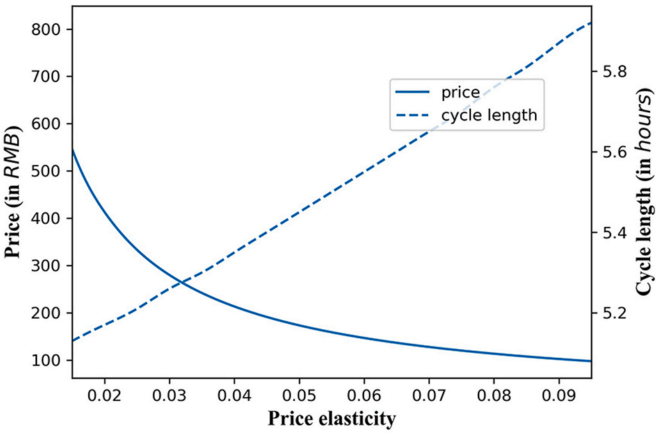

Fig. 5. The impact of the price elasticity on the optimal solutions.

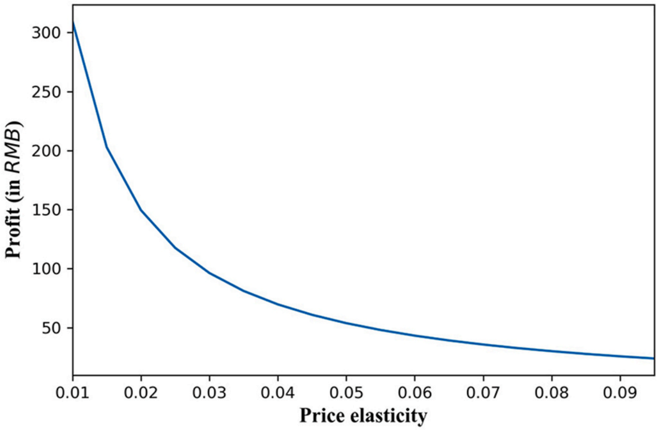

Fig. 6. The impact of the price elasticity on the profit.

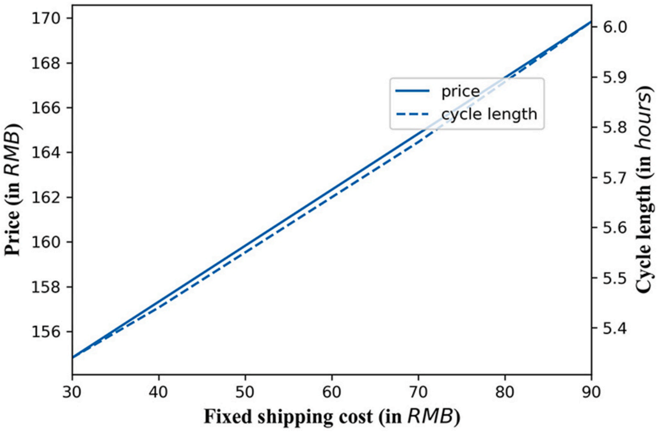

Fig. 9. The impact of the fixed shipping cost on the optimal solutions.

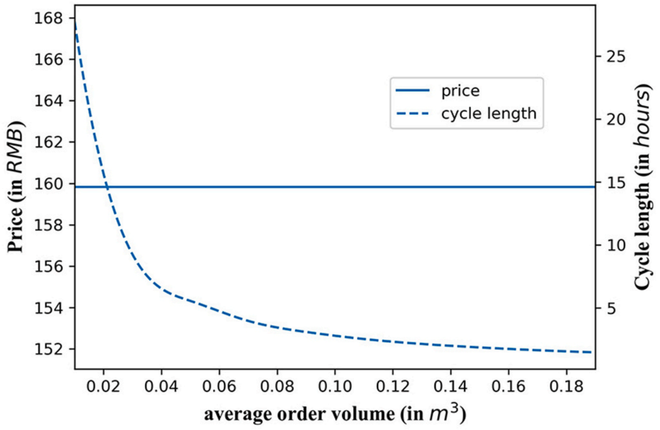

Fig. 7. The impact of the average order volume on the optimal solutions.

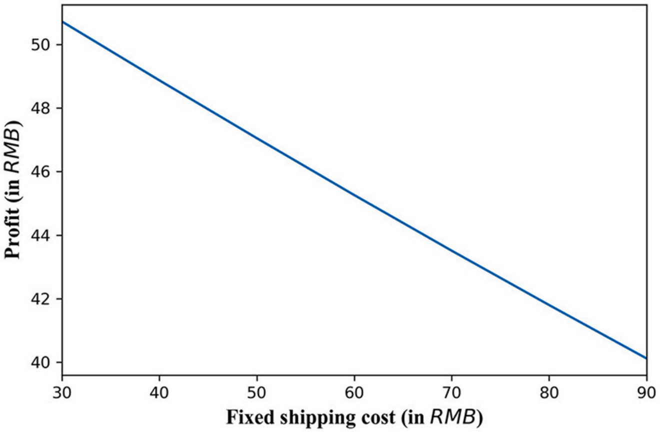

Fig. 10. The impact of the fixed shipping cost on the profit.

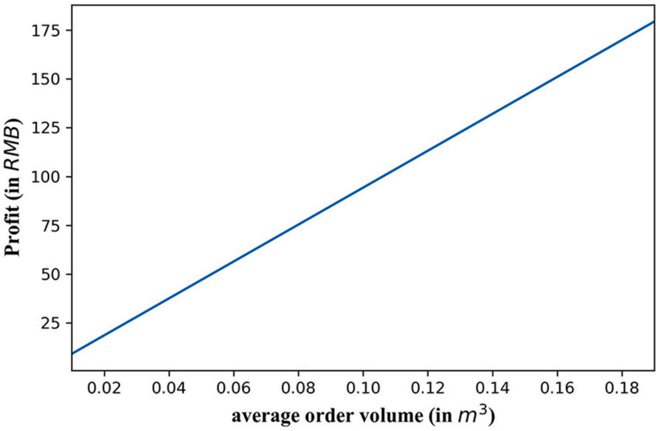

Fig. 8. The impact of the average order volume on the profit.

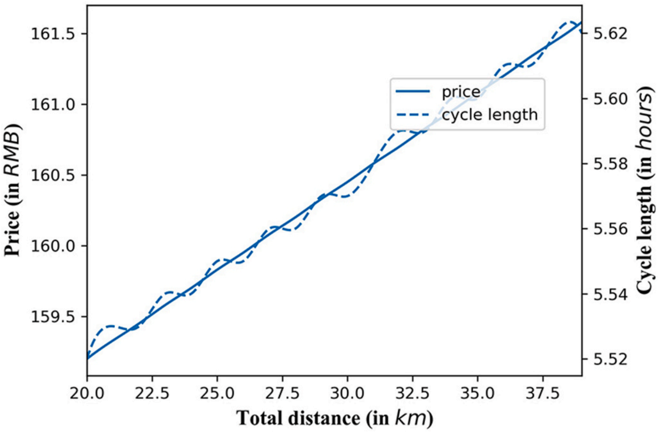

Fig. 11. The impact of the total distance on the optimal solutions.

By applying the additive model, we can obtain the optimal cycle length $T = 3.26$ h and the optimal price $P = 250.49$ RMB per unit volume. Thus the total profit is 148.24 RMB per unit time, which is increased by 23.53 % compared with the real operation data of company Y. Although a longer cycle length will lead to the increase of the holding costs, it can yield more profits. Thus, extending the cycle length can outperform other measures like simply reducing holding costs.

5.2. Sensitivity analysis

It is also important to understand the impact of different parameters on the equilibrium results. Here, we divide the parameters into three categories: market parameters, logistics parameters, and environment parameters.

Market parameters include the potential market size a, the price elasticity b and average order volume μ_v. First, we verify the impact of the potential market size a on the optimal solutions and the profit, which

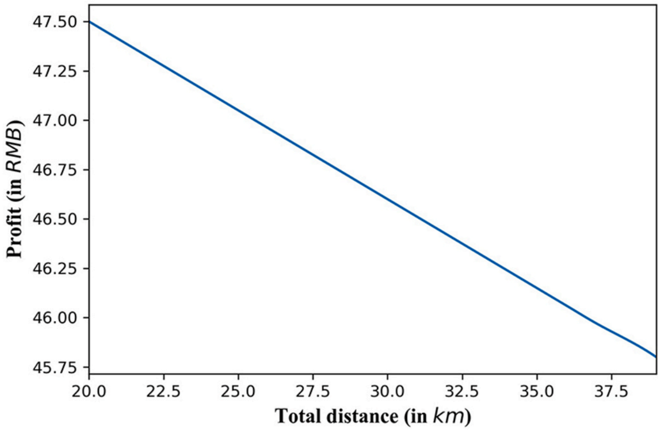

Fig. 12. The impact of the total distance on the profit.

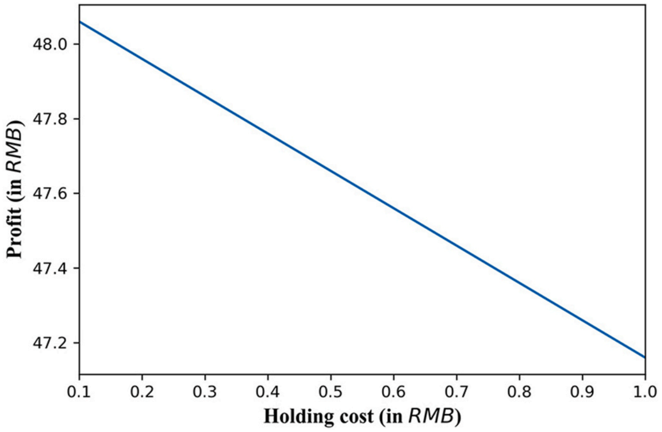

Fig. 13. The impact of the holding cost on the profit.

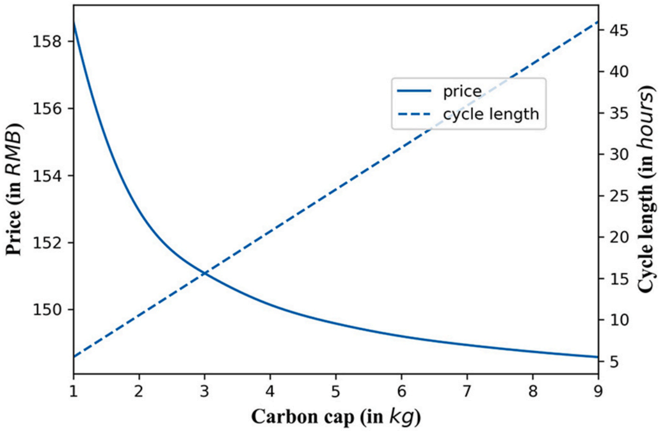

Fig. 14. The impact of the carbon cap on the optimal solution.

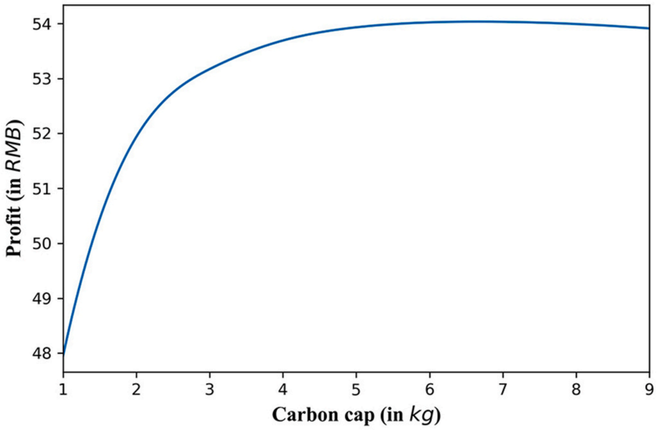

Fig. 15. The impact of the carbon cap on the profit.

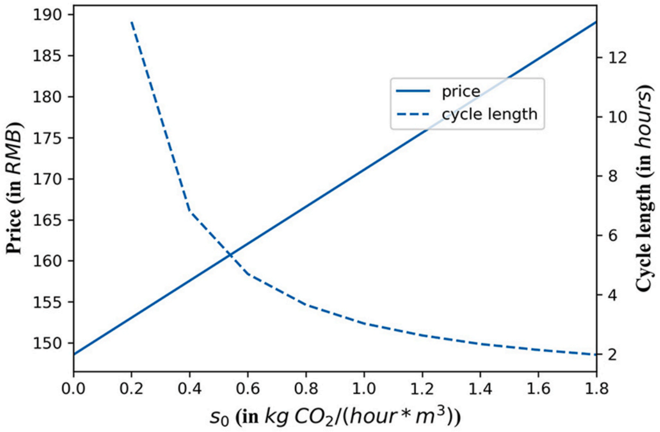

Fig. 16. The impact of s_0 on the optimal solutions.

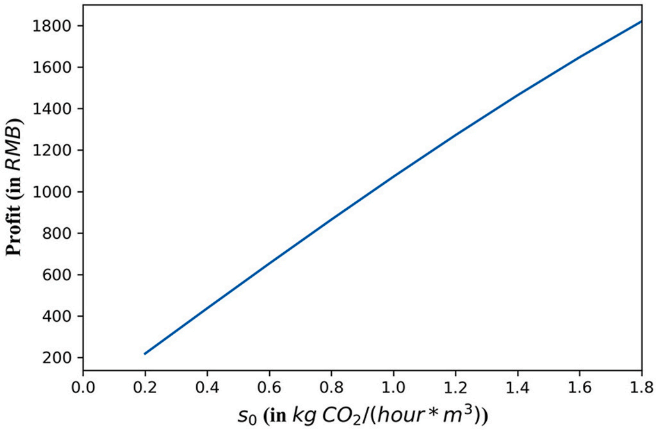

Fig. 17. The impact of s_0 on the profit.

is shown in Figs. 3 and 4. It shows that the optimal price and profit increase in the potential market size a while the cycle length decreases in a. When the cycle length turns out to be smaller, the growth rate of the profit becomes larger. It is worth mentioning that the profit and cycle length are significantly negatively affected by the potential market size a when a is small (such as $a = 1$), which is consistent with the practice of the O2O industry. At the early stage, when the platform enters the market, it cannot gain a positive profit since a large amount of investment needs to be made. Although the platform suffers a loss of profit by providing delivery services at the beginning, it can enlarge its market share.

Further, we examine the impact of different degrees of price elasticity, which are shown in Figs. 5 and 6. We find that the price and the profit both decrease in b while the cycle length increases in b. The growth rate of the cycle length fluctuates within a small range. Finally, from Figs. 7 and 8, we can see that the price is independent of μ_v. However, when μ_v increases, under the limited carbon cap, the platform has to shorten the cycle length to reduce holding costs for more profit.

Logistics parameters include the fixed shipping cost K, holding cost h, and the total distance d. From Figs. 9–13, we can find that both the price and the cycle length increase in K while the profit decreases in K. With the increase of the fixed shipping cost, the dispatched cycle length increases with a rate of less than 1 %, which means that the fixed shipping cost has a marginal impact on the cycle length. Moreover, we find that the optimal solutions does not depend on h, but the profit decreases in h. Further, both the optimal price and the cycle length increase in d, but the profits decrease in d. In other words, due to the increase in transportation distance, the platform has to extend the cycle length so that more goods can be delivered in a cycle. However, due to the increase of holding costs and transportation costs, the profit of the platform gradually decreases.

Environment parameters include the carbon cap C and s_0. From Figs. 14 and 15, we observe that both the cycle length and the profit increase in carbon caps C while the price decreases in C. The reason is that due to the increase in carbon cap C, the platform has a larger allowance of carbon emissions to transport more goods, which increases the cycle length T and results in more profit. As the carbon cap C further increases, the charged price P decreases and the holding cost increases, which results in a decrease in profit. From Figs. 16 and 17, we observe that both the charged price P and profits increase in s_0 while the cycle length T decreases in s_0. That means when s_0 increases, the platform tends to reduce the cycle length in order to satisfy the constraint of the carbon cap and increase the profit by increasing the charging price.

Further, taking the environment factor into consideration, the government assigns different carbon caps to different companies based on their type, scale, etc. However, in the carbon emission trading market, companies exceeding the assigned carbon caps can purchase carbon emission credits from companies with extra credits (Wang et al., 2019a, 2019b). Thus, we can extend our model to consider the carbon trading. For instance, we can add $c_0(C - s_0\mathbb{E}(V_n)\mathbb{E}(N(T)))$ into the objective function instead of having equation (7) as a constraint, where c_0 means carbon price per unit volume. Therefore, by optimally choosing the decision variables, the platform can decide whether to purchase extra carbon emission credits or not.

According to the above results, we summarize the key findings as follows.

(1) Pricing strategy is more sensitive to market parameters than to logistics parameters. For example, as Figs. 5 and 9 show, when the price elasticity b changes from 0.05 to 0.06, the price decreases by 16.93 % and the cycle length increases by 1.77 %. When the fixed shipping costs K changes from 50 to 80, the price increases by 4.69 %, but the cycle length increases by 6.13 %. Thus, when making pricing decisions, decision-makers should pay more attention to market conditions such as the potential market size and price elasticity than to internal capabilities such as the fixed shipping cost and inventory holding cost.

(2) At the start-up stage of an O2O freight platform, i.e., when the potential market size is small, market parameters influence the time decision more significantly than logistics parameters. When the potential market size rises to a certain degree (i.e., $a > 6$ in Fig. 3), logistics parameters have a greater impact on the time decision than market parameters. Thus, decision-makers should focus more on market trends at the early stage and on internal capabilities later.

(3) When the carbon cap C is at a low level, the profit of the platform increases with the increase of carbon cap. Due to the increase in carbon cap, the cycle length T can be extended, and the platform can transport more goods in one cycle. With the further increase of the carbon cap, the profit will reach a peak point, and then the profit will decline with the increase of the carbon cap. The reason is that the cycle length will become longer, which leads to an increase in holding costs, the profit of the platform will decrease. In this situation, we find that the high carbon cap actually hinders the sustainable development of the O2O platform. Thus, decision makers should appropriately reduce the carbon cap, which can not only increase the profit of the platform, but also protect the environment and benefit the sustainable development of the platform.

(4) The profit of the platform almost linearly changes with logistics parameters, and exponentially changed with market parameters. For example, when the price elasticity b decreases by 20 % (from 0.05 to 0.06), the profit decreases by 21.12 % (as shown in Fig. 6). While the fixed cost decrease by 20 % (from 50 RMB to 60 RMB), the profit only decreases by 3.80 % (as shown in Fig. 10). Thus decision-makers should focus more on market conditions than on internal capabilities. Specifically, a larger potential market size yields a higher profit margin while a higher price elasticity results in a lower profit.

(5) The O2O freight platform can be profitable only when the potential market size reaches a certain level, which means that the profit could be negative if the potential market size is small (e.g., $a = 1$ in Fig. 4). Thus, decision makers should sacrifice the short-term profit of the platform in exchange for a larger market share in the early stage.

In the context of O2O freight platform, our findings are different than the traditional transportation (Ursavas and Zhu, 2018). First, since the platform has a shorter lead time, which is more likely to lead to a negative profit in the early stage. Second, the proportion of holding cost in the platform is much smaller than traditional transportation due to the shorter lead time. Overall, Our theoretical contributions are as follows. (1) We explore the sustainable development of O2O freight platforms when make both pricing and dispatching time decisions by considering uncertain demand and carbon emission, which has not yet been studied in the literature. (2) A real data-set from an O2O freight platform in China has been applied to examine the model and the results show that our model is effective. We can find that market parameters are more sensitive to price, while logistics parameters are more sensitive to time. Further, environmental parameters have also a great influence on the optimal strategy and the profit. The managerial implications are as follows. In an O2O freight platform, when market parameters change dramatically, decision makers should be more careful about making the pricing decision. When the logistics parameters change greatly, decision makers should focus more on the time decision. Finally, to realize the sustainable development of the platform and maximize its profit, the carbon cap should be at an appropriate level.

6. Conclusion

This paper considers the optimal freight transportation planning of an O2O platform with uncertain demand and the carbon emission constraint. The platform receives customer orders online, gathers the goods offline in its own warehouse, and then delivers the goods to their destinations. The platform can maximize its profit by optimizing the dispatching time and pricing level under a carbon cap. We consider two demand models, i.e., additive model and multiplicative model, and then solve the optimization problems, respectively.

By applying a data set from a large O2O freight platform in China, we formulate an optimal strategy that can be valuable for business practices. The results show that the proposed strategy can effectively improve the revenue of the platform. We also carry out sensitivity analysis to explore the effects of market, logistics, and environment parameters. We find that market parameters have a more significant impact on pricing decision and the profit of the platform than logistics parameters, while logistics parameters affect the time decision of the platform more significantly than market parameters. With respect to environment parameters, the profit of the platform will first increase to a peak point as the carbon cap increases and then decline with the further increase of the cap. Thus, when making pricing decisions, decision-makers should pay more attention to market conditions such as the potential market size and price elasticity than to internal capabilities such as the fixed shipping cost and inventory holding cost. When making the time decision, decision-makers need to focus more on internal capabilities than market conditions. In terms of carbon emissions, decision makers need to set a reasonable carbon caps to obtain the maximum profit and achieve environment-friendly development. Moreover, the platform tends to suffer a negative profit at the start-up stage, to achieve sustainable development, which indicates that decision-makers should focus on the long-term development and endure the short-term loss.

We have gained the following managerial insights from this study. (i) The profit of the platform is more sensitive to market factors than logistics factors since market factors have a significant impact on profit margins. (ii) To gain a leading position at the early stage of entering the market, decision-makers should focus on market trends at the beginning and then the internal capabilities. (iii) A higher carbon cap does not necessarily result in more profits. In particular, the profit of the platform may even decrease with the carbon cap when the carbon cap is increased to a certain threshold. Thus decision makers should carefully consider the tradeoff between the allowance of carbon emission and profitability. (iv) When the carbon cap is large, the platform can sell the unused allowance of the carbon emission through the carbon emission trading market; when the carbon cap is small, the platform suffers a loss of the potential profit in order to meet the government regulation. (v) The platform can make profit only when the market size reaches a certain level. Thus, decision makers should sacrifice the short-term profit in exchange for a long-term sustainable development.

Our study contributes to the literature on O2O platform and freight transportation planning. However, there are several limitations. First, to address the issue of order punctuality, we can extend our model by including a constraint of delivery leadtime. Second, to concentrate on the pricing and dispatching problems of the O2O freight platform, we simplify the model by ignoring the last kilometer problem. However, we acknowledge that the last kilometer would be an interesting topic for further study.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Acknowledgements

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Appendix. Mathematical proofs

Proof of Lemma 4.1. For any given P, the second derivative of $\pi(T, P)$ with respect to T is given by

$$\frac{\partial^2 \pi(T,P)}{\partial T^2} = -2\frac{K}{T^3}.$$

Obviously, the second derivative of $\pi(T, P)$ is strictly negative, then the optimal cycle length T^* is uniquely obtained by the first derivative of $\pi(T, P)$. On the other hand, since $T \le \frac{C}{s_0\mu_v\lambda}$ is given by (9), if $\sqrt{\frac{2\ K}{h\mu_v\lambda}} > \frac{C}{s_0\mu_v\lambda}$, then the first derivative of $\pi(T, P)$ is strictly positive, thus $T^*(P)$ is an increasing function, and the optimal cycle length $T^* = \frac{C}{s_0\mu_v\lambda}$. Overall, $T^* = \sqrt{\frac{2\ K}{h\mu_v\lambda}}$ where $\sqrt{\frac{2\ K}{h\mu_v\lambda}} \le \frac{C}{s_0\mu_v\lambda}$ and $T^* = \frac{C}{s_0\mu_v\lambda}$ where $\sqrt{\frac{2\ K}{h\mu_v\lambda}} > \frac{C}{s_0\mu_v\lambda}$, QED.

Proof of Theorem 4.2. We first prove that there exists such a value P_0 satisfies the first derivative of $\pi(T(P), P)$ equals to 0. By perform the first derivative, we can obtain

$$\frac{\partial \pi(T(P),P)}{\partial P} = a\mu_v - 2bP + d\beta b\mu_v + \frac{hb\mu_v}{2}T + \frac{h\mu_v(a-bp)}{2}\frac{\partial T}{\partial P}.$$

1) If $\sqrt{\frac{2\ K}{h\mu_v\lambda}} \le \frac{C}{s_0\mu_v\lambda}$, the first derivative of $\pi(T(P), P)$ can be written as

$$a - 2bP + d\beta b + \frac{b}{2}\sqrt{\frac{hK}{2\mu_v(a-bP)}} = 0.$$

In order to clarify the nature of the first derivative of $\pi(T(P), P)$, we first obtain the second derivative of $\pi(T(P), P)$ as follows

$$\frac{\partial^2 \pi(T(P),P)}{\partial P^2} = -2b\mu_v + \frac{b^2}{8}\sqrt{2Kh\mu_v}(a-bP)^{-\frac{3}{2}}.$$

Obviously, when $0 \le P \le \frac{b}{a}$, $\frac{\partial^2 \pi(T(P),P)}{\partial P^2}$ is an increasing function. Because $\frac{\partial^2 \pi(T(P),P)}{\partial P^2}|_{P=P_u}$ is a positive value, then there exists a positive value $P_0 \in [0, P_u]$ satisfies $\frac{\partial \pi(T(P),P)}{\partial P}|_{P=P_0} = 0$. Thus we can obtain the function $\pi(T(P), P)$ is first strictly concave and then convex in $P \in [0, P_u]$. On the other hand, it is easy to learn that the expected profit tends to be zero when P approaches P_u. The approximate trend is shown in Fig. 18. We can find that the optimal price is $P^* = P_0$ if $P_0 > P_l$, otherwise $P^* = P_l$.

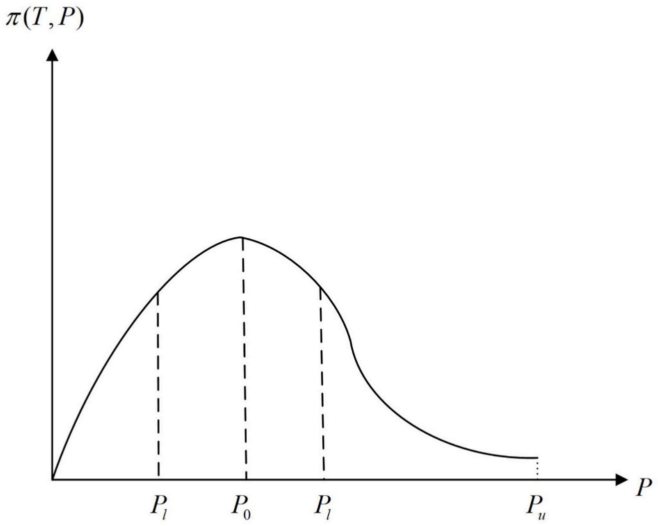

Fig. 18. The relationship between profit and price.

2) If $\sqrt{\frac{2\ K}{h\mu_v\lambda}} > \frac{C}{s_0\mu_v\lambda}$, we can follow similar procedure to obtain the conclusion (9), QED.

Proof of Theorem 4.3. The Proof consists of the following two parts.

1) For $\sqrt{\frac{2\ K}{h\mu_v\lambda}} \le \frac{C}{s_0\mu_v\lambda}$, we can obtain $P \ge (\frac{2aK\mu_v s_0^2}{hC^2})^{\frac{1}{b}}$. According to (10), it is easy to learn that $T(P) = \sqrt{\frac{2K}{h\mu_v\lambda}}$, then the objective expression can be written as follows

$$\pi(T(P),P) = (P-d\beta)\mu_v ap^{-b} - \sqrt{2Kh\mu_v aP^{-b}},$$

and the first derivative expression is

$$\frac{\partial\pi(T(P),P)}{\partial P} = a\mu_v P^{-b-1}\left(P - bP + d\beta b + \triangle P^{\frac{b}{2}}\right),$$

where $\triangle = b\sqrt{\frac{Kh}{2a\mu_v}}$. To analyze the property of the first derivative, we first need to explain the property of $f(P)$, where $f(P) = P - bP + d\beta b + \triangle P^{\frac{b}{2}}$.

(i) For $b < 2$, since $f(P)$ is strictly concave in P and $f(0) > 0$, it is clearly that there exists a value P_0 satisfies $f(P_0) = 0$. Then the unique optimal solution is $(T^*(P_0), P_0)$, where $P_l \le P_0$; otherwise, the unique optimal solution is $(T^*(P_l), P_l)$.
(ii) For $b = 2$, we can obtain $f(P) = \triangle P - P + 2d\beta$.

If $\triangle - 1 \le 0$, there exists a value P_0 satisfies $f(P_0) = 0$. Then the unique optimal solution is $(T^*(P_0), P_0)$, where $P_l \le P_0$; otherwise, the unique optimal solution is $(T^*(P_l), P_l)$.

If $\triangle - 1 > 0$, since $f(0) > 0$, then the first derivative $\frac{\partial\pi(T(P),P)}{\partial P}$ is an increasing function and the unique optimal solution is $(T^*(P_u), P_u)$.

(iii) For $b > 2$, $f(P)$ is strictly concave in P, denote $\overline{P}$ satisfies $f(\overline{P}) = 0$.

If $f(\overline{P}) \ge 0$, 34th first derivative $\frac{\partial\pi(T(P),P)}{\partial P}$ is always positive in P. Then $\pi(T(P), P)$ is increasing in P, and the unique optimal solution is $(T^*(P_u), P_u)$, where P_u is the upper bound of price.

If $f(\overline{P}) < 0$, the $\pi(T(P), P)$ is decreasing in P, then the unique optimal solution is $(T^*(P_l), P_l)$.

2) For $\sqrt{\frac{2\ K}{h\mu_v\lambda}} > \frac{C}{s_0\mu_v\lambda}$, we can obtain $P < (\frac{2aK\mu_v s_0^2}{hC^2})^{\frac{1}{b}}$ and $T(P) = \frac{C}{s_0\mu_v\lambda}$. Then the profit function can be written as

$$\pi(T(P),P) = (P-d\beta)\mu_v ap^{-b} - \frac{Ks_0\mu_v aP^{-b}}{C} - \frac{hC}{2s_0},$$

and the first derivative expression is

$$\frac{\partial\pi(T(P),P)}{\partial P} = \mu_v aP^{-b-1}\left(P - bP + d\beta b + \frac{Ks_0 b}{C}\right)$$

Denote $f(P) = P - bP + d\beta b + \frac{Ks_0 b}{C}$. The unique optimal solution can be divided into two cases.

(i) For $b \leq 1$, since $1 - b \geq 0$ and $f(0) > 0$, we can learn that the first derivative $\frac{\partial \pi(T(P),P)}{\partial P} > 0$, which means $\pi(T(P), P)$ is always increasing in P. Thus, the unique optimal solution is $\pi(T^*(P_l), P_l)$.

(ii) For $b > 1$, since $1 - b < 0$ and $f(0) > 0$, donating $\overline{P}$ satisfies $f(\overline{P}) = 0$, then we can know that $\frac{\partial \pi(T(P),P)}{\partial P}$ is first positive then negative in P. Thus the unique optimal solution is $(T^*(P_l), P)$, where $P_l \leq \overline{P}$; otherwise, the unique optimal solution is $(T^*(\overline{P}), \overline{P})$. QED.

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