



TOWARDS ENHANCING THE CROWDSOURCING DOOR-TO-DOOR DELIVERY: AN EFFECTIVE MODEL IN BEIJING

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ABSTRACT. Door-to-door delivery is becoming more prevalent in practice. However, crowdsourcing couriers' uncertainties (delivery distance, monthly income, and the monthly volume of tasks) make it hard for logistics companies to maintain a stable crowdsourcing couriers' participation rate and guarantee a good level of delivery coverage rate. To solve this problem, this paper proposed the crowdsourcing delivery optimization model, which considers the bounded rationality of crowdsourcing couriers, analyses the crowdsourcing couriers' participation rate under three crowdsourcing couriers' uncertainties, and helps logistics companies to decrease the delivery cost by adjusting the delivery price per parcel and delivery distance while guaranteeing a certain level of delivery coverage rate. Further, this paper combined the whale optimization algorithm (WOA) with the model to design a heuristic algorithm for solving the crowdsourcing delivery problem. The experiments were conducted according to a data set from Beijing (China). Experiment results shows that 4.07 million USD a month is enough to provide door-to-door delivery services in 94.22% area of the city, which is feasible for giant companies.

1. Introduction. Global e-commerce has been developing continuously and rapidly. Especially, e-commerce revenue in China is expected to grow to 1.553 billion U.S. dollars in 2025 [1]. China's rapid increase in the e-commerce market has also led to the rapid development of the offline express market. According to the State Post Bureau of China, by the end of 2019, the express business had surpassed 60 billion parcels, and total delivery parcels reached 83.36 billion in 2020 [2]. Such rapid development of express business suggests the huge potential of the express business, but also brings huge pressure to the delivery phase, especially in last-mile delivery.

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China Express-Mail Services (EMS) receives nearly 500 million orders every day, although over a million full-time couriers work for EMS, customers' demands are still hard to satisfy. Moreover, plenty of parcels would be left at temporary storage points, customers need to pick up the parcels by themselves, reducing customer satisfaction.

Many logistics companies have begun participating in "last mile delivery" to improve customer satisfaction. According to a global investigation [3], the door-to-door delivery mode will become the most important and fastest-growing transportation mode in the "last mile delivery" strategy. Many countries have made great efforts to enhance the door-to-door delivery mode. In Japan, the home delivery sales value of community-based retail co-ops is approximately 2.09 trillion Japanese yen [4]. In the United States, 25 percent of respondents reported their store was planning to add online grocery home delivery or store pickup services in 2020 [5]. In South Korea, 99.3 percent of survey respondents had used delivery services in the past three months [6]. Especially in China, the door-to-door delivery mode was widely used [33, 30]. However, the biggest challenge for logistics providers in last-mile delivery is cost in some countries [34], and the extensive use of crowdsourcing couriers to participate in delivery tasks can greatly reduce costs. Many companies hire crowdsourcing couriers for door-to-door delivery. Ren-ren Express Company (China) now has millions of part-time couriers and full-time users. It provides intra-city delivery and purchase services in more than 50 cities in China, and generates tens of thousands of orders every day. Founded in Shanghai in 2014, Dada group is China's leading local real-time retail and distribution platform. Based on the flexibility and expansibility of the crowdsourcing network, Dada group has built a distribution service system composed of landing distribution, real-time distribution, and help buy and deliver to meet the surge of order demand in diversified scenarios to provide professional and efficient local real-time delivery services for all kinds of businesses and individual users. Since the first quarter of 2020, the delivery business of Dada express has covered more than 2400 counties, districts, and cities in China, with a daily single volume peak of more than 9.2 million in 2019.

As a last-mile delivery strategy, door-to-door delivery should maintain an adequate coverage rate to grab the market. However, because of the uncertainty of crowdsourcing couriers, it is hard to calculate the number of crowdsourcing couriers and delivery coverage rate. Some literature shows that higher awards, easier tasks, longer duration, and lower competition intensity would attract a higher number of crowdsourcing couriers [35]. Therefore, this paper studies three impact factors: delivery distance, monthly income, and the monthly volume of tasks, which caused the uncertainty of crowdsourcing couriers. We also propose an effective crowdsourcing door-to-door delivery model to quantify the number of crowdsourcing couriers and calculate the delivery coverage rate. This paper considers adjusting the three influencing factors to ensure a certain level of delivery coverage rate, and further reduce the distribution cost.

In summary, the contributions of this paper include the following:

- (1) Considering the bounded rationality [11] of crowdsourcing couriers, this paper designs the formulations to calculate the impact of three impact factors (the delivery distance, the monthly income, and the monthly volume of tasks) on the participation rate of crowdsourcing couriers.

(2) A crowdsourcing door-to-door delivery model is proposed, and three novel calculation methods are designed to quantitatively calculate the number of crowdsourcing couriers, delivery coverage rate, and delivery cost respectively.

(3) According to the characteristics of the crowdsourcing door-to-door delivery model, the improved W-OA algorithm is proposed in this paper, and the experimental results verify the effectiveness and efficiency of the proposed algorithms

The remainder of the paper is structured into four sections. Section 2 presents a literature review of last-mile delivery and crowdsourcing delivery; Section 3 presents a crowdsourcing door-to-door delivery model; Section 4 introduces WOA; in section 5, the simulation data, the results, analysis, conclusions, and limitations are provided.

2. Literature review. The crowdsourcing delivery problem is a very complex problem which can be informed by literature on last-mile delivery, logistics transportation problems, and scheduling problems. Especially in last-mile delivery research, crowdsourcing delivery was chosen as an effective mode to enhance the last-mile strategy.

Some new technologies and equipment were considered by scholars to enhance the last-mile delivery. For example, Lemardel Clément combined UAV and ground autonomous transportation equipment to participate in the last mile delivery [19], and Michele D. Simoni proposed robot assistant methods in the last mile delivery [37]. Although these research methods can effectively promote the delivery of the last mile in theory, they are relatively complex and expensive to implement and are easily affected by the infrastructure construction in different areas, such as UAV charging stations and other equipment. Further, they are difficult to implement widely in a short time.

The large-scale establishment of package lockers is also considered an effective solution to solve the last-mile delivery problem, and methods for effectively using parcel lockers were proposed by [21, 41, 20, 24]. However, the large-scale establishment of parcel lockers requires a lot of expenses, and the maintenance of the parcel lockers requires a lot of manpower and material resources. What needs more attention is that, if customers fail to pick up the package from parcel lockers in time, the storage pressure of the parcel lockers will increase, which will affect the delivery speed.

In recent years, a sustainable concept was researched by scholars in last-mile delivery strategy [36, 16]. Based on the concept of sustainability and sharing, widely using social idle vehicles and part-time couriers were considered by some researchers to enhance the last mile delivery [46]. For example, Kulińska [17] proposed widely used ride-sourcing services in last-mile delivery. Chen [10] proposed a crowdsourcing integrated transportation as a new form of the citywide passenger-package delivery system. Wang [42] proposed a large-scale crowdsourcing delivery method for the last mile delivery. The efficiency of logistics and satisfaction of customers were improved by crowdsourcing delivery. However, the application of crowdsourcing delivery in last-mile delivery also has some challenges. Castillo [9] pointed out that, compared with full-time couriers, when the time window is tight and the delivery task is heavy, crowdsourcing couriers will perform worse. Most of the literature on crowdsourcing delivery focused on the optimizing delivery route of crowdsourcing vehicles or matching problems between couriers and tasks [8]. The literature on

impact factors for crowdsourcing delivery is few. For example, Hakim Akeb [7] proposed a crowdsourcing delivery model for parcels, but ignored the impact of other factors such as the volume of tasks, which is impractical. Huang [14] showed the importance of studying some impact factors of crowdsourcing couriers. However, there is no quantifiable solution to them, and no quantitative research on the impact of these factors on crowdsourcing delivery.

Based on existing works, this paper builds a crowdsourcing delivery model to quantify the participation rate and the delivery coverage rate of a specific area, further using the WOA to help the company design the delivery distance and delivery gain per parcel for crowdsourcing delivery couriers.

3. Model.

3.1. Problem description. The traditional delivery mode requires couriers to deliver packages to the pick-up points, and customers need to pick up packages by themselves. This paper considers a large-scale crowdsourcing delivery mode that depends on a large number of crowdsourcing couriers to pick up parcels from the pick-up point and deliver them to the customers. Figure 1 shows the two modes of last-mile delivery.

However, compared with full-time job couriers, the crowdsourcing couriers have more autonomy to decide whether to receive the delivery task released by the platform, which would bring more uncertainty to last-mile delivery, which makes it hard for this mode to maintain a certain number of couriers to complete the delivery task, and delivery coverage rate also cannot be guaranteed. Fortunately, we found that couriers' desire to receive tasks can be affected by some major factors, monthly income, delivery distance, and volume of tasks. In other words, by controlling these three factors, crowdsourcing couriers' participation rate and delivery coverage rate can be improved.

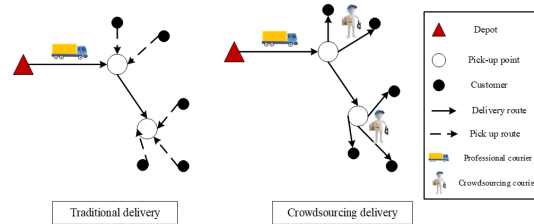


FIGURE 1. Traditional delivery and crowdsourcing delivery mode

This paper is focused on the last-mile delivery problem in the urban area and sets up a large-scale delivery model that considers participation rate under three impact factors (monthly income, delivery distance, and volume of task) and designed the WOA to decrease the delivery cost by adjusting the delivery distance and gain per parcel. For convenience, this paper makes some assumptions and descriptions as follows:

(1) For convenience, urban population density is all the same and equals the average population density. The difference in population density is not considered in this paper. When the unified density crowdsourcing delivery mode is set properly, extending to different areas with different population densities is easy. This paper

assumes that the number of parcels required by each urban resident is equal to the average number of parcels of urban residents. This paper can establish an equivalence relation between the number of parcels delivered and the delivery area. The delivery area reflects the number of parcels delivered by crowdsourcing couriers.

(2) Three main impact factors (monthly income, delivery distance, and monthly task volume) are considered in this paper, while other tiny impact factors and individual cases are not considered in this paper. Participation in crowdsourcing delivery can be defined as the psychological state in which people are ready to completely dedicate themselves to an act, many factors can impact the psychological state, and this paper focuses on some main factors that are feasible for companies to adjust. The impact factors of crowdsourcing participation include two aspects: intrinsic motivation and extrinsic incentives, and intrinsic motivation and external incentives are widely practiced as motivational strategies in various practices [15, 39, 45]. Compared with the traditional delivery mode or management problems [43, 22, 23], the crowdsourcing delivery mode provides a more flexible choice to decide whether accept the delivery task or not, which means if crowdsourcing couriers feel the tasks take too much of their time and energy, based on the self-determination theory, the willingness to participate in crowdsourcing delivery will reduce. Thus, this paper takes task volume and delivery distance as important impact factors. External incentives are always provided by logistics companies; gain per parcel is the most effective factor to attract crowdsourcing couriers, and is chosen as an impact factor in this paper.

(3) The crowdsourcing couriers are bounded by rationality, meaning that the crowdsourcing couriers' willingness to accept the delivery task is different because of different levels of income, delivery distance, and task volume. In other words, the willingness of crowdsourcing couriers is a kind of satisfaction rather than a specific request for income, delivery distance, and task volume. Thus, properly adjusting the three impact factors would both maintain a certain level of participation rate and decrease the delivery cost.

3.2. Variables and parameters. To set up the door-to-door delivery model, some variables were defined in this paper. Because the data of some variables such as the total number of packages and income of crowdsourcing couriers fluctuate greatly every day and may have a big gap from couriers to couriers, we set such a rule for all variables: total number of packages to be delivered in the area, which is represented by the parameter N_{par} is the average number of parcels per month; the monthly income of crowdsourcing couriers, which is represented by g_{crowd} is the average income of all crowdsourcing couriers per month. Table 1 shows the meanings of variables and parameters. The delivery gain per parcel g_{par} and the delivery radius r are two decision variables. Decision variables can affect the average monthly income g_{crowd} and the number of parcels delivered by per crowdsourcing couriers per month N_{par}^{crowd} , which can be shown in formulas (1) to (4).

3.3. Crowdsourcing door-to-door delivery model. This section is separated into three subsections to describe the large-scale delivery model: calculation of delivery distance, calculation method of the impact under three factors, and calculation of crowdsourcing delivery coverage rate. Formulations (1) to (4) are proposed by Hakim Akeb [7], and formulations (5) to (11) are all originally proposed in this paper.

TABLE 1. Optimization results of the cases

Variables or Parameters	Meaning
g_{par}	The delivery gain per parcel
r	The delivery radius of couriers
N_{par}	Total number of packages that need to be delivered in the area
N_{crowd}	The number of potential crowdsourcing couriers on the platform
N_{actual}	The actual number of crowdsourcing couriers involved in the delivery
N_{par}^{crowd}	Number of parcels delivered by per crowdsourcing couriers per month
D	Population density
P	Total number of residents in the area
S	The area of urban
P_r	Number of customers within the delivery radius
δ_{income}	Impact factor of crowdsourcing couriers' monthly income on the participation rate
$\delta_{distance}$	Impact factor of crowdsourcing couriers' delivery distance on the participation rate
δ_{task}	Impact factor of crowdsourcing couriers' volume of tasks on the participation rate
δ	The participation rate of crowdsourcing couriers on the platform
K	The set of income level of the city
k	The index in set K
M_{ave}^k	The k_{th} level average monthly income of residents in the city
L_{max}	The maximum acceptable delivery distance of crowdsourcing couriers
L_{refer}	The average delivery distance of full-time job couriers
C_{crowd}	The maximum acceptable volume of tasks for crowdsourcing couriers
g_{crowd}	The average monthly income of crowdsourcing courier
α	The crowdsourcing door-to-door delivery coverage rate
Q	The total cost of crowdsourcing delivery
$n_{distance}$	Sensitivity coefficient of crowdsourcing couriers to the delivery distance
n_{income}	Sensitivity coefficient of crowdsourcing couriers to the monthly income
m_i	The proportion of the i th level monthly income of residents in the city
n_{task}	The monthly task volume per crowdsourcing courier
η_{task}	The monthly task volume aversion coefficient of crowdsourcing couriers
Φ	The target delivery coverage rate of logistic company
∂	The maximum delivery volume of tasks per crowdsourcing courier

3.3.1. *Calculation of delivery radius.* This paper separates the urban community area into small circular parts, which is the delivery area of crowdsourcing couriers. If there are enough people involved in crowdsourcing distribution, the undelivered area between tangent circular distribution areas will become very small, and in the actual delivery process, crowdsourcing delivery couriers can undertake the majority of delivery tasks and send full-time delivery couriers to delivery remainder points so that the door-to-door delivery service can cover the whole distribution area. The delivery area of crowdsourcing delivery couriers is shown in Figure 2.

According to the model proposed by Hakim Akeb[7], the delivery radius can be calculated by formulas (1)-(4).

The number of customers within the radius P_r depends on the population density D and the surface of the concerned area πr^2 . P_r is calculated by formula (1).

$$P_r = \pi r^2 D \quad (1)$$

The number of monthly parcels delivered by crowdsourcing couriers is calculated by formula (2), which is a product of average parcels per customer and the number of customers within the delivery radius.

$$N_{par}^{crowd} = \frac{N_{par}}{P} P_r = \frac{\pi D N_{par}}{P} r^2 \quad (2)$$

The monthly income of crowdsourcing couriers can be obtained from the gain of the individual parcel and the number of parcels delivered by crowdsourcing couriers per month, see formula (3).

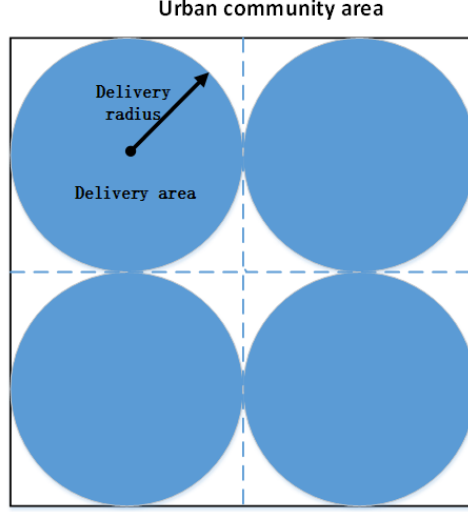


FIGURE 2. Crowdsourcing delivery area

$$g_{crowd} = N_{par}^{crowd} g_{par} = \frac{\pi D N_{par} g_{par}}{P} r^2 \quad (3)$$

Then, according to formula (3), the delivery radius of crowdsourcing couriers is obtained in formula (4).

$$r = \sqrt{\frac{g_{crowd} P}{\pi D N_{par} g_{par}}} \quad (4)$$

3.3.2. Calculation method of the impact under three factors. In this subsection, the calculation methods of the impact of some factors on the participation rate of crowdsourcing couriers are proposed. They are delivery distance, monthly income, and volume of tasks. According to rational bounded decision theory [29], people often do not have a clear calculation of the utility value in decision-making, but screen relatively satisfactory decision-making schemes, which need some reference values. Based on the rational bounded decision theory, the calculation methods of the impact of three impact factors (delivery distance, monthly income, and monthly task volume) are as follows.

(1) The delivery distance

Delivery distance is important for crowdsourcing couriers. Most of the crowdsourcing couriers just use their spare time to deliver, long-distance delivery distance means that crowdsourcing couriers would spend more time and energy, which may decrease the participation willingness of crowdsourcing couriers, and according to a rule of thumb, within a certain delivery distance, crowdsourcing couriers are not sensitive to distance. Thus, the impact of crowdsourcing couriers' delivery distance on participation rate is calculated by the formula (5) and formula (6).

$$\delta_{dis\ tan\ ce} = \begin{cases} 1, & \text{if } r < L_{refer} \\ \left(\frac{L_{\max} - r}{L_{\max} - L_{refer}} \right)^{n_{dis\ tan\ ce}}, & \text{if } r \geq L_{refer} \end{cases} \quad (5)$$

$$n_{dis\ tan\ ce} = \frac{r}{L_{\max}} \quad (6)$$

Here, L_{refer} is the average delivery distance of full-time job couriers, and $L_{\max}$ is the maximum acceptable delivery distance of crowdsourcing couriers. If the delivery distance r does not surpass the value L_{refer} , the delivery distance is acceptable for crowdsourcing couriers. If the delivery distance r surpasses the value L_{refer} , some crowdsourcing couriers may refuse to deliver parcels, and the participation rate will decrease. Considering the delivery distance's cumulative effect on crowdsourcing couriers, the sensitivity coefficient of crowdsourcing couriers to the delivery distance $n_{dis\ tan\ ce}$ is proposed in this paper to adjust the downtrend of the participation rate. With the increase in delivery distance, the participation rate will accelerate to decline. The variation trend of the participation rate with crowdsourcing delivery distance is shown in Figure 3.

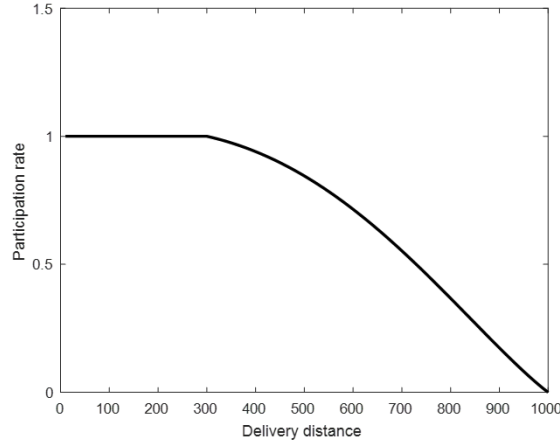


FIGURE 3. Impact of delivery distance on the participation rate

Assuming $L_{refer} = 300$, this means that the average delivery distance of full-time job couriers is 300 m, and the variation curve of the delivery participation rate with the delivery distance is shown in Figure 3. As shown in Figure 3, if the delivery distance is within 300 meters, the participation rate of crowdsourcing couriers is not sensitive to the increase of delivery distance, but when the delivery distance surpasses 300 meters, with the increase of the delivery distance, the participation rate of crowdsourcing delivery couriers decreases exponentially.

(2) The monthly income

The monthly income of crowdsourcing delivery couriers also has an important impact on the participation rate. From a monthly income perspective, when people decide whether to accept the task of crowdsourcing delivery, will refer to the monthly income of their current monthly income level. In other words, low-income people are more likely to accept crowdsourcing delivery tasks to improve their income and

are more sensitive to monthly income fluctuations. However, people with higher monthly income levels are less likely to accept crowdsourcing delivery tasks and less sensitive to monthly income fluctuations because the crowdsourcing delivery monthly income accounts for a low proportion of these people's monthly income. Therefore, people with different income levels have different sensitivity to monthly crowdsourcing delivery income, and this paper introduces the income sensitivity coefficient n_{income} to reflect the crowdsourcing delivery monthly income sensitivity of people with different monthly income level. M_{ave}^k is the k th level average income of residents in the city. The impact of crowdsourcing couriers' delivery income on participation rate is calculated by formulas (7) - (9).

$$\delta_{income} = \sum_i^{k-1} m_i + m_k n_{income} Q_k, k \in K, M_{ave}^{k-1} < g_{crowd} \leq M_{ave}^k \quad (7)$$

$$Q_k = \begin{cases} \exp((g_{crowd} - M_{ave}^k)), & g_{crowd} < M_{ave}^k \\ 1, & else \end{cases} \quad (8)$$

$$n_{income} = \begin{cases} 1, & if g_{crowd} \geq M_{ave}^k \\ \frac{g_{crowd}}{M_{ave}^k}, & if g_{crowd} < M_{ave}^k \end{cases} \quad (9)$$

Formula (7) is the participation rate calculation formula, which includes two parts. This paper classified the monthly income into K levels, and M_{ave}^{k-1} to M_{ave}^k are the corresponding average income levels. The first part $\sum_i^{k-1} m_i$ is the cumulate participation rate, where m_i is the proportion of the i th level income groups. If the monthly income of crowdsourcing couriers is between M_{ave}^{k-1} and M_{ave}^k , people whose monthly income is lower or equal to M_{ave}^{k-1} will participate in crowdsourcing delivery. The second part targets the k th income level group, $k \in K$. With the increase of the crowdsourcing delivery monthly income, the increase rate of the participation rate will accelerate, this paper chooses exponential growth mode to reflect this phenomenon. m_k is the proportion of the residents with k th level monthly income, Q_k is the monthly income satisfaction degree calculated by the formula (8). In order to make a more realistic reflection of the actual situation, the monthly income sensitivity coefficient n_{income} which is calculated by formula (9) is used to adjust the increasing trend, meaning that if the crowdsourcing monthly income is less than the k th level average monthly income of residents in the city, the crowdsourcing monthly income is not attractive.

Take the monthly income level of Beijing in 2020 as an example, and the proportion of the i th level monthly income of residents in the city m_i 20%. The average monthly income of residents is divided into five grades: 316.13 USD / month, 558.49 USD / month, 796.5 USD / month, 1095.85 USD / month, and 1816.70 USD / month. According to the formulas from (7)-(9). The variation trend of the participation rate with crowdsourcing monthly income is shown in Figure 4.

As can be seen in Figure 4, although the participation rate of crowdsourcing couriers increases as the monthly income of crowdsourcing couriers increases, the rate increase continues to slow down. For instance, the monthly income required to increase the participation rate of crowdsourcing couriers from 60% to 90% is almost double the monthly income required to increase the delivery rate from 0 to 60%. Therefore, for companies that provide crowdsourcing delivery services, continuously increasing the monthly income of crowdsourcing delivery couriers cannot improve

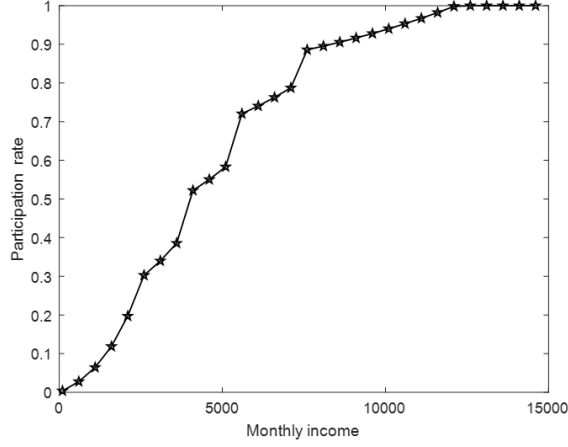


FIGURE 4. Impact of monthly income on the participation rate

the participation rate, and sometimes becomes a high-cost but low-performance method. Designing a reasonable monthly income can both guarantee a certain level of participation rate and reduce the cost of companies.

(3) Tasks

Generally speaking, the attitude of crowdsourcing couriers to the monthly delivery task volume is negative. With the increase in the monthly delivery task volume, the crowdsourcing couriers would need more time and energy, which will reduce the participation willingness of crowdsourcing couriers, and the crowdsourcing delivery couriers' participation rate will decrease.

Especially, when the number of monthly tasks exceeds the acceptable value of crowdsourcing delivery, the aversion of crowdsourcing delivery couriers will increase. This paper introduces the monthly task volume aversion coefficient η_{task} to reflect the phenomenon: if the monthly task volume exceeds the acceptable value C_{crowd} , with the increase in the monthly task volume, the crowdsourcing couriers would become more averse to monthly delivery tasks and the crowdsourcing participation rate will decrease faster. Formulas (10) to (12) are designed by this paper to describe the monthly task volume's impact on the participation rate.

$$\delta_{task} = \begin{cases} e^{(-\frac{n_{task}}{C_{crowd}})}, & \text{if } n_{task} \leq C_{crowd} \\ \eta_{task} * e^{(-\frac{n_{task}}{C_{crowd}})}, & \text{if } n_{task} > C_{crowd} \end{cases} \quad (10)$$

$$n_{task} = \frac{g_{crowd}}{g_{par}} \quad (11)$$

$$\eta_{task} = \frac{C_{crowd}}{n_{task}} \quad (12)$$

Formula (10) indicates that when the monthly task volume of the crowdsourcing couriers is within the maximum acceptable volume of tasks for crowdsourcing couriers C_{crowd} , the participation rate decreases exponentially with the increase of monthly tasks. When the task volume of the current month exceeds C_{crowd} , the task volume aversion coefficient η_{task} is introduced in this paper to adjust the decreasing trend of the participation rate. Formula (11) is the calculation method of the monthly task volume of crowdsourcing delivery couriers, and crowdsourcing

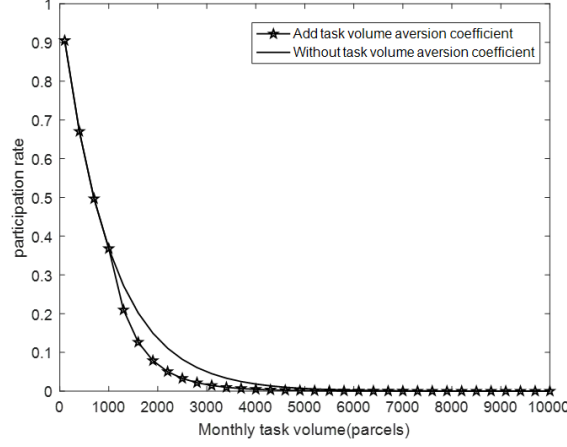


FIGURE 5. The volume of tasks harms the participation rate

delivery couriers are paid according to the number of parcels, so the monthly task volume of crowdsourcing delivery couriers is equal to the divided monthly income crowd g_{crowd} by the gain per parcel g_{par} , and formula (12) is the calculation method of the task aversion coefficient η_{task} : with the increase of monthly task volume, the aversion to distribution tasks will gradually increase and η_{task} will decrease, which will accelerate the decrease rate of participation rate.

Assuming that the crowdsourcing deliverer can accept 1000 parcel delivery tasks every month, according to formulas from (10) to (12), the variation curve of crowdsourcing couriers' participation rate with monthly task volume is shown in Figure 5.

3.3.3. Calculation of crowdsourcing delivery coverage rate. Logistics companies that provide crowdsourcing door-to-door delivery services will be more concerned about the proportion of urban areas covered by crowdsourcing door-to-door delivery services after the application of the crowdsourcing door-to-door delivery mode, which will affect the effectiveness of crowdsourcing door-to-door delivery services. Therefore, it is necessary to evaluate the proportion of the door-to-door crowdsourcing delivery mode in an urban area and to make corresponding adjustments in time. The calculation methods of crowdsourcing delivery coverage rate are as follows:

$$\delta = \delta_{distance} \delta_{income} \delta_{task} \quad (13)$$

$$N_{actual} = \begin{cases} \delta N_{crowd}, & \text{if } \delta N_{crowd} * n_{task} \leq N_{par} \\ \frac{N_{par}}{n_{task}}, & \text{if } \delta N_{crowd} * n_{task} > N_{par} \end{cases} \quad (14)$$

$$\alpha = \frac{\pi r^2 N_{actual}}{S} \quad (15)$$

Formula (13) indicates that the actual participation rate of crowdsourcing delivery couriers after considering three factors is equal to the product of the distribution distance, the task volume, and the monthly income impact factors, meaning that people decide whether to accept the crowdsourcing delivery task or not would

consider both of these factors. Formula (14) indicates the actual number of crowdsourced delivery couriers who can accept the delivery task. When the available delivery capacity is less than the total delivery task volume required, all crowdsourcing delivery couriers are chosen for crowdsourcing delivery. When the available delivery capacity surpasses the total delivery task volume required, we select the number of couriers corresponding to the total delivery task volume required, which equals dividing the total number of packages delivered by the monthly task volume per crowdsourcing courier. Formula (15) indicates the crowdsourcing delivery coverage rate, which is equivalent to dividing the total delivery area by the whole urban area.

3.3.4. Crowdsourcing delivery cost optimization model. According to Simon's bounded rationality and prospect theory [29] which suggests that human decisions are based on their limited cognition instead of optimizing for the best possible outcome, people often settle for a satisfactory solution that meets their needs. Thus, different groups have different satisfaction standards for crowdsourcing delivery. In the field of logistics, after conducting extensive interviews with frontline couriers, some literature has found that delivery platforms should establish reasonable reward and punishment strategies for delivery personnel to ensure their continuous participation in the delivery process. Otherwise, it will reduce the delivery participation rate [32]. Some literature found the participation rate of couriers may be affected by delivery-related information (such as delivery distance, and tasks) [25, 38], and some literature has found that delivery participation is closely related to fairness or satisfaction [13, 12], which may be associated with the delivery distance, delivery gain [31] or delivery tasks. According to bounded rationality theory, different groups will have different perceptions of fairness and trust toward different delivery strategies, affecting the delivery couriers' decision to participate in the crowdsourcing delivery process. However, there are significant differences in satisfaction with delivery among different groups. The difference in satisfaction can facilitate the logistics companies to reasonably arrange the task volume for the crowdsourcing delivery couriers and the delivery gain per parcel. In terms of the crowdsourcing delivery model, crowdsourcing couriers are paid according to the number of delivery parcels and delivery gain per parcel, so the monthly income of crowdsourcing couriers depends on the number of tasks and the delivery gain per package, and the task volume depends on the delivery distance of the crowdsourcing delivery couriers. Thus, the delivery gain per parcel and the delivery distance of the crowdsourcing couriers can adjust the participation rate of the crowdsourcing couriers.

The crowdsourcing delivery cost optimization model is as follows:

$$Q = N_{actual} * g_{par} * \pi * r^2 * D * N_{par}^{crowd} \quad (16)$$

$$Q' = \begin{cases} (\Phi - \alpha) N_{par} g_{par}, & \text{if } \Phi > \alpha \\ 0, & \text{else} \end{cases} \quad (17)$$

$$Min \quad Q + Q' \quad (18)$$

$$st \quad \alpha \geq \Phi \quad (19)$$

$$n_{task} \leq \partial \quad (20)$$

$$N_{actual} \leq N_{crowd} \quad (21)$$

Formulas (16) – (18) represent the objective function of the optimization model. When public package delivery can meet coverage requirements, the cost is calculated as the product of the actual number of crowdsourcing couriers in crowdsourcing delivery and the monthly income of crowdsourcing delivery couriers. When the delivery coverage rate is lower than the target coverage rate α , the remaining delivery tasks will increase the delivery price for additional delivery, increasing the delivery cost.

Formulas (19) – (21) are the constraint functions. Formula (19) indicates that the delivery coverage rate should meet the target. Formula (20) indicates that the monthly task volume of crowdsourcing delivery couriers should be within the maximum delivery volume of tasks per crowdsourcing courier. Formula (21) suggests that the number of people participating in crowdsourcing delivery shall not surpass the number of potential crowdsourcing couriers on the platform.

4. Method. This paper selects an algorithm from the existing literature adapted to solve the large-scale crowdsourcing delivery model. In 2016, based on simulating the strategy of whales in the process of predation [26], the whale optimization algorithm (WOA) was proposed as a new heuristic intelligent optimization algorithm [27] and was applied in many fields [28, 44], and through a large number of test function tests and comparative experiments [26], the effectiveness of the WOA has been proved. Thus, this paper uses the WOA to simulate the process of large-scale crowdsourcing delivery problem.

This paper used real number encoding to represent a solution. Assuming that the whale population size is N and the dimension of solutions is 2, the i th solution can be expressed as $X_i = (x_i^1, x_i^2)$, $i = 1, 2, \dots, N$. The first dimension of the solution represents the delivery gain per parcel g_{par} , and the second dimension of the solution represents the delivery radius r .

The WOA mathematically describes the bubble spitting and predation process of whales, that is, two iterative mechanisms: contraction and spiral search mechanism. They are described as follows:

(1) Shrink search mechanism:

Like other heuristic algorithms, there is no prior knowledge of the global optimal location in the search space before solving the optimization problem. The contraction search mechanism in the WOA algorithm takes the optimal position in the current population as the prey position, and other whale individuals in the population surround the optimal individual. The specific encirclement mechanism is shown in formulas (22) - (25):

$$X(t+1) = X_p(t) - A * |C * X_P(t) - X(t)| \quad (22)$$

$$A = 2 * a * r_1 - a \quad (23)$$

$$C = 2 * r_2 \quad (24)$$

$$a = 2 - 2 * \frac{t}{t_{\max}} \quad (25)$$

Here, $X_p(t)$ is the optimal solution in the t_{th} iteration, parameters r_1 and r_2 are two random numbers, and the parameter a is called the iteration step control parameter, which decreases with the number of iterations. With the increase of iteration, the parameter a decreases linearly from 2 to 0.

(2) Spiral search mechanism:

In the spiral position updating method, the iterative search is realized by simulating the spiral motion of whales in the process of foraging. The specific iteration mechanism is shown in formulas (26) to (27).

$$X(t+1) = D' * e^{bl} * \cos(2\pi l) + X_p(t) \quad (26)$$

$$D' = |X_p(t) - X(t)| \quad (27)$$

In formula (26), the parameter b is a constant which is used to define the shape of the logarithmic spiral, and the parameter l is the random number in $[-1,1]$. Formula (27) represents the distance between the current solution and the individual optimal value, which is used to simulate the predation process of whales approaching their prey with a spiral trajectory. It should be noted that the two mechanisms of whales in the process of predation exist at the same time, that is, whales swim around the contraction circle of prey and follow the spiral path at the same time. To simulate this behavior, in the optimization process, the whale algorithm runs these two mechanisms with 50% probability. To enhance the ability of the algorithm to jump out of the local optimal solution, the algorithm will also conduct a random search. The search method is shown in formula (28).

$$X(t+1) = X_{rand}(t) - A * |C * X_{rand}(t) - X(t)| \quad (28)$$

Here X_{rand} is the individual position vector randomly selected in the solution space, and the other parameter variables are the same as formula (22). The process of WOA is as follows:

First, a whale population with a population number of n is randomly generated in the search space to form an initial population, and various parameters required for the iteration of the mechanism are set.

Then, in the process of evolution, the group randomly selects a whale individual according to the location of the current individual's optimal whale as the reference location for the next iteration update. The iterative search is determined according to the size of the random number with the range from 0 to 1. If the random number is less than or equal to 0.5, the individual whale carries out the contraction search mechanism; Otherwise, the individual whale carries out whale spirals search mechanism.

Finally, the WOA algorithm is iterated until the termination condition is satisfied. The process of WOA is shown in Figure 6.

This paper proposes a crowdsourcing delivery algorithm based on the WOA algorithm and the mathematical model, and the details are shown in Algorithm 1.

5. Simulation results and conclusion.

5.1. Data collection. This paper chooses data from Beijing in 2020 [47] as the data set to simulate the crowdsourcing process. The target delivery coverage rate is set at 90%. The basic information of the data set required by the model is shown in Table 2.

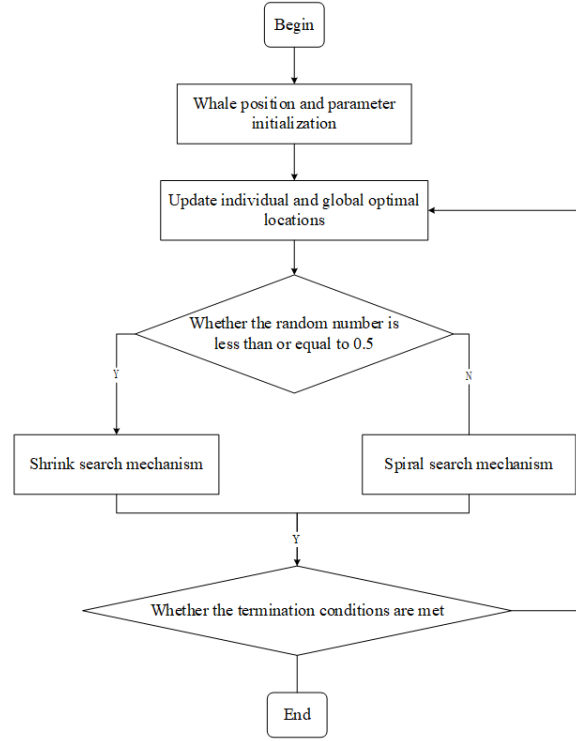


FIGURE 6. The process of WOA

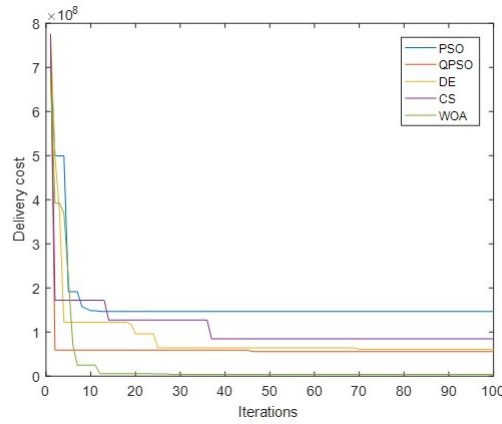


FIGURE 7. Iterative convergence curve of algorithms

5.2. Results. As shown in Figure 7, compared to other algorithms, the WOA algorithm has faster convergence speed and optimization ability.

All algorithms were implemented in Matlab2016b and ran on a Windows 10 64bit PC with a 2.10GHz CPU and 16GB RAM. The algorithm proposed in this paper is designed to combine with the model. The WOA is chosen to update the solution,

Algorithm 1 Optimization algorithm

-
- 1: Initialize parameters and determine the maximum number of iterations t_{max} and population size P .
 - 2: **while** $t < t_{max}$ **do**
 - 3: **while** $i < P$ **do**
 - 4: For the i_{th} individual in the population, calculate the impact factor of crowdsourcing couriers' monthly income δ_{income} , delivery distance $\delta_{distance}$, volume of tasks δ_{task} by formulas (1) - (12), and the delivery coverage rate α by formulas (13) - (15).
 - 5: **if** $\alpha > \Phi$ **then**
 - 6: The cost is calculated by formula (16).
 - 7: **else**
 - 8: In addition to crowdsourcing delivery cost, delivery tasks that do not meet the standards will be handed over to traditional delivery personnel at a fixed price by formula (17), and the total delivery cost is the sum of these two parts.
 - 9: **end if**
 - 10: $i = i + 1$
 - 11: **end while**
 - 12: Updating individual optimal values and global optimal values with minimum cost
 - 13: Updating the parameters according to formulas (23) - (25).
 - 14: Generate a random decimal a between 0 and 1
 - 15: **if** $a \geq 0.5$ **then**
 - 16: Updating the solutions according to formula (22).
 - 17: **else**
 - 18: Updating the parameter D and solutions according to formulas (26) - (28).
 - 19: **end if**
 - 20: Repair infeasible solutions
 - 21: $t = t + 1$
 - 22: **end while**
-

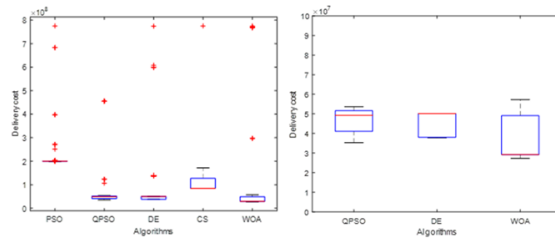


FIGURE 8. Optimization results with different algorithms

and the calculation of other fitness values and the repair strategy of the solution is adapted to the model. To verify the effectiveness of the WOA, this paper has added several heuristic algorithms, including particle swarm optimization (PSO), quantum particle swarm optimization (QPSO), differential evolution (DE), and cuckoo search

TABLE 2. Basic experimental parameters value

Index	Value
α	90
N_{par}	8614.4(10000 pieces / month)
D	1041(<i>person/km</i> ²)
P	2153.6(10000 persons)
S	16,140(<i>km</i> ²)
M_{ave}^1	315.71(USD/month)
M_{ave}^2	557.71(USD/month)
M_{ave}^3	795.39(USD/month)
M_{ave}^4	1094.39(USD/month)
M_{ave}^5	1814.27(USD/month)
m	0.2
L_{max}	5km
C_{crowd}	1,000(pieces/month)
N_{crowd}	1680.9(10000 persons)
$N_{\text{par}}^{\text{crowd}}$	0-10(CNY/piece)
t_{max}	100
b	2
r_1	Random number in [0,1]
r_2	Random number in [0,1]
l	Random number in [-1,1]

(CC) as algorithms for updating solutions to test the effectiveness of the WOA, and comparative experiment results are shown in Figure 7 and Figure 8.

As shown in Figure 8, it can be seen that, overall, compared to other algorithms, the WOA method has better solving performance, with most of the decomposition distributed around the minimum value, demonstrating good search ability. The fluctuation range of the WOA solution is slightly larger than that of the QPSO algorithm and DE algorithm, but most of the decomposition of these two algorithms is distributed in the upper bound. The minimum value is significantly higher than that of the WOA, indicating that the WOA has a stronger ability to jump out of local optima and has more opportunities to search for better solutions. This section will simulate the large-scale crowdsourcing delivery in Beijing according to the algorithms and examples designed in Section 4.

The logistics company guarantees the target delivery coverage rate and reduces the delivery cost by changing the delivery gain per parcel and delivery distance (or delivery area). The reasonableness of the model is verified by analyzing the recorded cost change curve and relevant delivery information.

According to the whale optimization algorithm and the crowdsourcing delivery example designed in Section 4, on the premise of ensuring the delivery rate required by the logistics company, taking the lowest cost as the objective function, taking the delivery gain per parcel and the delivery distance of crowdsourcing couriers as the decision variables, and recording the minimum cost and average delivery cost in each iteration, as shown in Figure 7, the basic results of the crowdsourcing delivery optimization model are shown in Table 3.

TABLE 3. Basic results of the crowdsourcing delivery optimization model

Index	Value
The number of couriers participating in crowdsourcing delivery	49335
Delivery distance of crowdsourcing delivery personnel	313(m)
The delivery area of each crowdsourcing courier	0.31(km^2)
The number of customers to be served by each crowdsourcing courier	321(persons)
Delivery gain per parcel	0.05USD/parcel
Monthly task volume of each crowdsourcing courier	1645(parcel)
Monthly income of crowdsourcing couriers	82.51(USD)
The monthly cost paid by the logistics company	4,073,160(USD)
Delivery coverage rate	94.22%

As shown in Table 3, a total of 49,335 crowdsourcing delivery couriers from Beijing were willing to participate in crowdsourcing delivery. The crowdsourcing delivery distance is 313 m, which is acceptable to the crowdsourcing delivery couriers, and the number of customers that each crowdsourcing courier needs to serve every month is 1645, which is acceptable for crowdsourcing couriers. The delivery area is 0.31 km^2 , and the value is about the area of a Chinese community, which means the crowdsourcing couriers can deliver parcels in their community. Logistics companies only need to invest 4.07 million USD a month to provide door-to-door delivery services in 94.22% of the city, which is feasible for giant companies. The provision of crowdsourcing delivery services in Beijing reflects that large-scale crowdsourcing delivery services in Beijing can be implemented.

5.3. The analysis of the cost under different targets of delivery coverage rate. This section analyzes the cost under different targets of delivery coverage, which reflect the cost advantage of crowdsourcing door-to-door delivery. This paper further analyses the cost performance of crowdsourcing door-to-door delivery in Beijing.

The traditional delivery mode needs additional cost for door-to-door delivery, generally 0.1493 USD/parcel, according to the data set in Table 3, and based on the door-to-door crowdsourcing delivery model and WOA, this paper sets 100 delivery coverage rates from 1% to 100%, as targets of delivery coverage rate, and calculates the cost of traditional delivery mode and crowdsourcing delivery mode.

For research convenience, this paper uses a quadratic polynomial fitting method with 100 crowdsourcing delivery cost values to fit a curve of crowdsourcing delivery costs as shown in Figure 9. The relationship between crowdsourcing delivery cost and target coverage rates can be approximately obtained as follows:

$$Q=417 * \alpha^2+8290 * \alpha-56105 \quad (29)$$

As shown in Figure 9, the cost of the crowdsourcing delivery mode is lower than the traditional delivery mode, which reflects the huge cost advantage of the door-to-door crowdsourcing delivery mode. With the increase in the delivery coverage rate, the cost advantage is more obvious. With the increase of the delivery coverage rate, compared with traditional delivery mode, crowdsourcing delivery mode can save more cost. For example, when the delivery target is 10%, the crowdsourcing delivery mode needs 1,229,800 USD, the traditional delivery mode needs 1,286,100 USD,

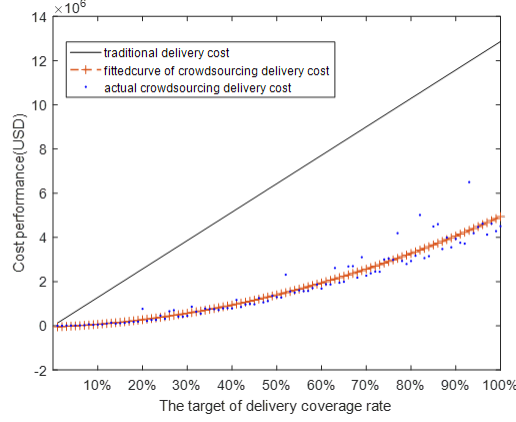


FIGURE 9. Curve of the cost under different targets of delivery coverage

and crowdsourcing delivery mode saves 56,300 USD. When the delivery target is 70%, the crowdsourcing delivery mode needs 6,733,600 USD, the traditional delivery mode needs 9,002,700 USD, and the crowdsourcing delivery mode saves 3,269,100 USD.

5.4. The analysis of the rationality of crowdsourcing couriers. Similar to the cost analysis, this paper separately uses 100 crowdsourcing delivery gains and 100 crowdsourcing couriers' monthly incomes to fit a curve of crowdsourcing delivery gains under different targets of delivery coverage rates, as shown in Figure 10, and a curve of crowdsourcing couriers' incomes under different targets of delivery coverage rates, as shown in Figure 11. The relationship between crowdsourcing delivery gains and crowdsourcing couriers' incomes under different target coverage rates can be approximately obtained as formula (30) and formula (31).

$$g_{par} = 0.007 * \alpha + 0.0017 \quad (30)$$

$$g_{crowd} = 13.11 * e^{0.02 * \alpha} \quad (31)$$

As shown in Figure 10 and Figure 11, crowdsourcing couriers participate in door-to-door delivery not just for increasing monthly income, but also to expect high rewards per parcel. Results shown in Figure 9 strengthened the conclusions of existing literature [7, 18, 40], which propose a conception that reward plays a vital role to attract crowdsourcing couriers to participate in door-to-door delivery. However, the delivery gain per parcel is always ignored to be considered with monthly income simultaneously. Thus, the result of this paper expanded an important conclusion that, to increase the delivery coverage rate, both the monthly income and delivery gain per parcel need to be increased.

The delivery gain per parcel and monthly income determined the delivery distance and monthly task volume of crowdsourcing couriers, and, after all, the increase in monthly income and the decrease of gain per parcel means the task volume and delivery distance would increase, which will add to the work time of crowdsourcing

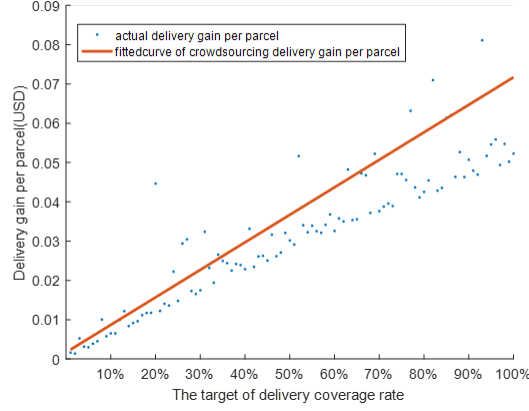


FIGURE 10. Curve of the delivery gain under different targets of delivery coverage

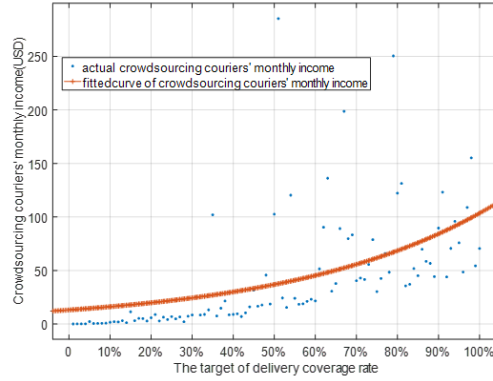


FIGURE 11. Curve of monthly incomes under different targets of delivery coverage

couriers, and may lead to the low willingness to take the delivery jobs and finally decreases the delivery coverage rate.

Further, this paper analyzes the number of crowdsourcing couriers, task volume, and delivery distance under different delivery coverage targets, and results are separately shown in Figure 12, Figure 13, and Figure 14.

As shown in Figure 12, to increase the delivery coverage rate, more crowdsourcing couriers in society need to participate in crowdsourcing door-to-door delivery strategy, and the number of crowdsourcing couriers is growing rapidly, which is the core concept and advantage of the crowdsourcing delivery mode.

As shown in Figure 13, with the increase of the delivery coverage target, the monthly task volume increases but is constrained to an acceptable and reasonable range, which in most situations is no more than 2000 parcels per month. Owing to the number of crowdsourcing couriers increasing and delivery gain per parcel

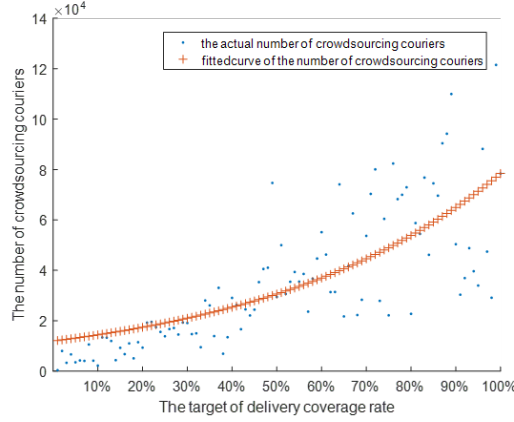


FIGURE 12. Curve of the number of crowdsourcing couriers under different targets of delivery coverage

increasing, the monthly task volume can be constrained to an acceptable level that does not impact the crowdsourcing couriers' participation willingness too much.

As shown in Figure 14, the delivery distance of crowdsourcing couriers decreases rapidly, from nearly one mile to under 300 meters, which is more convenient for crowdsourcing couriers to deliver parcels.

From Figure 9 to Figure 14, all results reflect such a phenomenon that crowdsourcing delivery couriers are bounded by rationality, and not just attracted by monthly income signal; however, compared with traditional full-time job couriers, crowdsourcing couriers are more complex, they have preferences in high monthly income and gain per parcel, and low delivery distance and little monthly task volume.

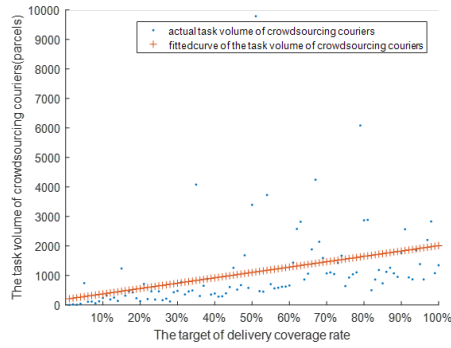


FIGURE 13. Curve of the monthly task volume of crowdsourcing couriers under different targets of delivery coverage

6. Conclusions. This paper establishes a large-scale crowdsourcing delivery model. The crowdsourcing delivery model established in this paper mainly aims at door-to-door delivery services and considers the effects of delivery distance, delivery task

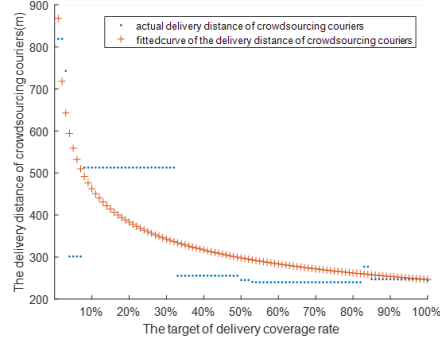


FIGURE 14. Curve of the delivery distance of crowdsourcing couriers under different targets of delivery coverage

volume, and income on crowdsourcing delivery. Six parts are included in this paper: the calculation method of the delivery distance, the calculation methods of the influence of three factors (crowdsourcing delivery radius, delivery distance, delivery task) on the crowdsourcing delivery effect, and the crowdsourcing calculation model of delivery coverage rate and the crowdsourcing delivery cost. Through the crowdsourcing delivery model proposed in this paper, logistics companies can design the delivery gain per parcel and delivery distance to both guarantee the delivery coverage rate and decrease the delivery cost of the crowdsourcing delivery process; these theories are very important for the public who provide crowdsourcing delivery services.

There are some limitations of this paper. The population densities used are an average density for the urban area, but in real situations, the population densities are always changing from the central to the edge of the city. Additionally, the capabilities and delivery radius of different kinds of crowdsourcing couriers (such as drivers and cyclists) are assumed the same, but they are different in reality. In future work, dynamic population density and the difference in capabilities and delivery radius between crowdsourcing couriers should be considered.

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