scientific reports

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New approaches and performance analysis of on-demand delivery systems using buses

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With the rapid growth of on-demand delivery, traditional third-party delivery services using electric bicycles face increasing challenges, including increased labor costs and safety issues. To address these issues, we propose two modes for on-demand delivery systems using buses. One is the "bus terminal + professional crowd shippers" (B&P) mode, which involves consolidating parcels from various origins at the bus transfer hub. From there, they are grouped and delivered by buses. The other is the "bus stop + crowdsourced passenger" (B&C) mode, which transports parcels directly from the origin to the destination by passengers without the need for consolidation and sorting at bus transfer hubs. Both modes fully utilize the surplus capacity of buses and employ resources from retail stores and third-party shippers. We evaluated these modes using key performance indicators (KPIs) such as labor costs, cost increases from en-route destination changes, and average delivery time per kilometer. This analysis was based on 18,349 delivery cases in downtown Ningbo, China. Through this evaluation, we identified the strengths, weaknesses, opportunities, and threats associated with each mode. Our findings reveal that both the B&P and B&C modes effectively reduce delivery costs and external impacts while maintaining a user experience and efficiency level comparable to traditional third-party delivery services for mid-to-long-distance (3–10 km) deliveries. However, the use of public transportation may limit the flexibility of the delivery mode. Based on these insights, we provide strategic recommendations for the further development and implementation of B&P and B&C modes.

The demand for efficient, rapid, and customized delivery services has driven the rapid development of on-demand delivery characterized by small batches and multiple deliveries[1]. However, with the increase in on-demand delivery demand, issues such as increased empty mileage for riders and non-standard driving behaviors have emerged in the third-party on-demand delivery mode[2]. These issues lead to high delivery costs and traffic congestion, making the current on-demand delivery mode unsustainable[2–4]. This paper will analyze the practical application potential of bus participation in on-demand delivery to address these issues.

With a strategic focus on prioritizing public transportation development, the bus system has undergone improvements, including the expansion of an extensive network and continuous increases in operating speeds[5]. The improvements in the public transportation system, along with its inherent high frequency and timeliness, make it particularly well-suited for the on-demand delivery services, which are characterized by small batch sizes and frequent deliveries[6]. Furthermore, the low cost, low energy consumption, and environmentally friendly characteristics of public transportation make it a potential solution to address the issues associated with on-demand delivery[7].

This research defines on-demand delivery systems using buses as a specialized urban logistics solution that utilizes buses for parcel delivery. This approach incorporates buses into the on-demand delivery market, along with additional auxiliary delivery facilities, to transport various goods, including medicine, everyday essentials, and personal items, from origin to destination.

The on-demand delivery systems using buses involves multiple stakeholders, including bus companies and passengers as suppliers, and logistics companies and individual consumers as demanders. Existing research has largely focused on the relationship between bus companies and logistics companies[8–10], as well as the supply–demand matching between passengers and logistics companies[6,11]. These two cooperation modes usually led by logistics companies, which are responsible for coordinating delivery needs and developing specific delivery plans, while bus companies or passengers act as auxiliary resources, undertaking some of the fixed delivery tasks[12,13].

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These modes can improve delivery efficiency and reduce costs to some extent by integrating bus company station resources and unused capacity and utilizing passengers' predetermined travel routes[6,11].

However, research on the collaboration between bus companies and individual consumers, as well as between passengers and individual consumers, remains limited. Given that consumer delivery needs often arise spontaneously and are challenging to plan or schedule in advance. Therefore, it is necessary to explore effective connection methods between bus companies (or passengers) and individual consumers to enable successful coordination and storage of parcels. This can include identifying suitable parcel storage solutions and coordinating the various participants in the delivery process. Effective connections will enable the bus system's resources to be utilized efficiently while responding quickly to delivery demands.

This paper proposes two on-demand delivery systems using buses to investigate the feasibility of matching between bus companies and individual consumers, and between individual consumers and passengers. This study considers the coordination and cooperation among various participants by utilizing traditional third-party delivery services to connect bus companies with customers and a parcel temporary storage station to link customers with bus passengers. We have provided a detailed implementation plan and process for each delivery mode, fully utilizing the relevant resources of the public transportation system while comprehensively considering cost and technical constraints during implementation.

To evaluate the implementation effect of the on-demand delivery mode, this paper establishes key performance indicators (KPIs) from four aspects: delivery cost, efficiency, service experience, and external impact, focusing on the interests of all participants. These KPIs comprehensively assess the performance and applicable conditions of the proposed on-demand delivery mode.

Literature review
Forms of delivery modes by bus
Recent research has explored various approaches to integrating public transportation infrastructure, such as bus routes, stations, and vehicles, into on-demand parcel delivery systems. These studies aim to leverage the existing capacity and reach of bus networks to improve delivery efficiency and sustainability.

Bruzzone et al. propose a freight-on-transit (FOT) system that involves coordination between bus companies, transfer hub personnel, and other transportation modes to complete delivery tasks. The authors develop a multi-commodity network model to determine optimal package transportation routes based on freight volume and economic considerations. However, while the mode excels in route optimization, it lacks attention to the crucial aspect of customer interaction, leaving a gap in the connection between the delivery system and end consumers[14].

Similarly, Cheng et al. introduce a parcel delivery mode that utilizes the idle capacity of urban bus systems. They design delivery routes and ensure that parcels are unloaded during peak hours to minimize disruption to passengers. Despite successfully reducing interference with passenger experience, this mode requires significant human resources to load and unload parcels at transfer stations, increasing operational costs and reducing efficiency[8].

Mourad et al. offer a more technologically advanced approach by integrating PD (Parcel Delivery) robots with buses. In this mode, PD robots transport parcels to bus stops, after which the goods are carried on buses to another stop. The same robot then delivers the parcel to its destination. While this mode takes delivery time windows into account, it faces challenges with timing, as the robot and bus must arrive at the stop simultaneously. This lack of buffer time significantly reduces the mode's success rate[9].

In addition to these modes, Zhang et al. explore the potential of involving passengers in the delivery process. Their survey indicates that most passengers are willing to participate in parcel delivery, provided they receive adequate compensation[11]. Wyrowski et al. propose a "public transportation congestion transportation" mode, where bus passengers act as couriers, transporting parcels between package storage lockers located at bus stations. This approach efficiently connects passengers with parcel delivery by using these lockers as transfer nodes. Although the cost of installing package storage lockers at bus stops is not high, this mode requires the installation of storage lockers at every bus stop to implement the solution. This will result in significant costs, which will also limit the scalability of the solution[6].

In summary, while these modes demonstrate the viability of using buses for on-demand parcel delivery, they face significant challenges. Issues related to customer connectivity, labor intensity, and timing constraints need to be addressed to ensure efficient and cost-effective solutions. Moreover, most existing studies focus on the relationship between logistics companies and bus operators, with less emphasis on direct interactions with consumers or passengers. This gap highlights the need for further research into more seamless and scalable delivery modes that effectively coordinate the various participants, particularly in spontaneous, consumer-driven delivery scenarios.

Evaluation indicators for on-demand delivery
An evaluation indicator system is a crucial tool for measuring the performance of a delivery mode. Currently, few studies have established comprehensive evaluation indicator systems for on-demand delivery. However, in related articles focusing on the design of on-demand delivery, one or two indicators may be selected to assess the advantages and disadvantages of the delivery mode. These studies evaluate on-demand delivery from various perspectives. To offer a more intuitive view, we categorize these indicators into four aspects: delivery cost, delivery efficiency, user experience, and external influence, as presented in Table 1.

Current research has proposed delivery indicators that include both qualitative[8,17,18] and quantitative[11,12,16] measures. Although existing indicators cover various aspects, several issues remain.

1) Lack of assessment of the bus system: Existing evaluation indicators focus solely on the delivery aspect, without considering the impact of bus participation on both the bus system and the delivery system. It is

Category	Evaluation indicators
Delivery cost	Labor costs[11]; implementation cost[15]; fuel cost[16]; transportation cost[12]
Delivery efficiency	Speed[8]; successful delivery rate; transportation time cost[16]; service time[10];
Delivery experience	Delivery capacity[8]
External influence	Pollution emissions[11]; environmental benefits[15]; reducing congestion levels[17,18]; impact of logistics moves[17]; carbon emissions[17]; emission cost[16]

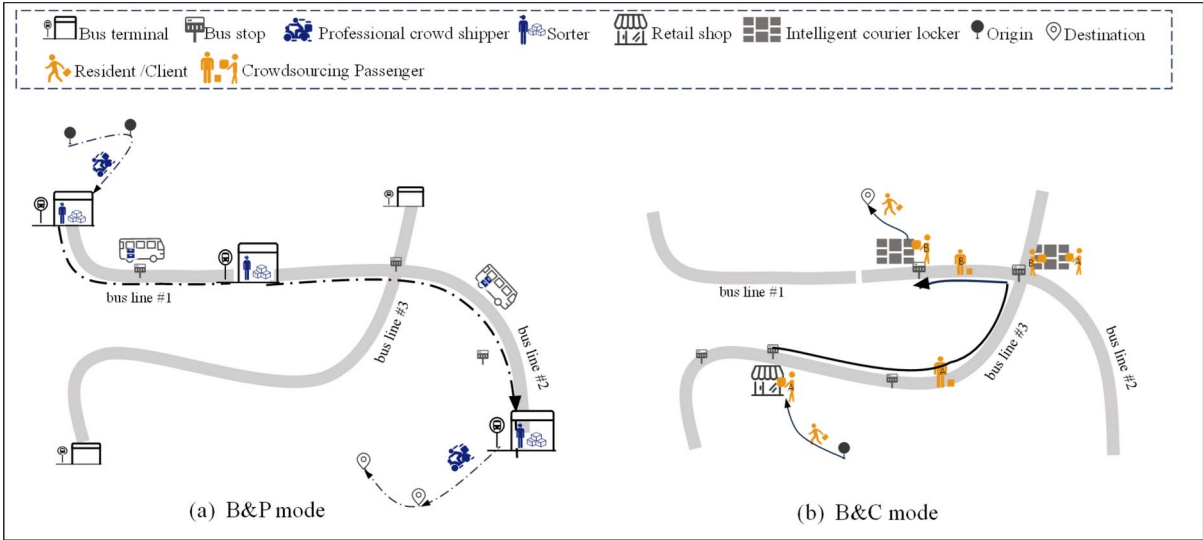**Table 1**. Evaluation indicators for on-demand delivery.

Fig. 1. Illustration of the B&P and B&C mode delivery setup.

important to consider how utilizing the bus system for on-demand deliveries might affect the bus system itself, such as the impact on its facilities and equipment[11]. Additionally, the inherent characteristics of the bus system, such as fixed routes, should be considered to understand how they influence the dynamics of on-demand delivery when buses are involved.

2) Lack of comprehensiveness: Current research typically evaluates the on-demand delivery mode involving bus participation from a single or limited perspective, such as delivery speed and service quality. No comprehensive evaluation has been carried out to integrate various evaluation perspectives into a systematic and comprehensive evaluation index system. To address this, evaluation indicator systems could be established by combining different evaluation dimensions, and different emphases could be matched to different dimensions.

3) Ambiguity in indicator definitions and calculations: Some indicators proposed in current research lack clear definitions[17,18], and specific calculation methods[18], resulting in evaluation standards that are not reproducible.

Framework of two on-demand delivery modes

This chapter introduces two on-demand delivery modes, "bus terminal + professional crowd shippers (B&P)" and "bus stop + crowdsourced passenger (B&C)" to examine the possibility of connecting bus companies with individual customers, and customers with passengers (Fig. 1).

In the B&P mode, parcels are consolidated from various origin points and transported to the bus transfer hub, from which they are grouped and delivered by buses. The delivery process involves three main participants: the bus company, the sorter at the bus terminal, and professional crowd shippers from third-party platforms. When a delivery is requested, customers hand their parcels to professional crowd shippers, who then collect all parcels from their designated starting points and transport them to the bus terminal. At the bus terminal, sorters categorize the parcels by destination and place them in an independent express locker on the bus. During transit, parcels can be transferred at both bus terminals, with sorting managed by the sorter. Upon reaching the destination's bus terminal, the sorter unloads the parcels, which are then passed to professional crowd shippers for final delivery. Due to the limited number of bus transfer hubs in this mode, it becomes easier to control costs and manage resources.

In the B&C mode, parcels are transported directly from the origin to the destination by crowdsourced passengers without the need for consolidation and sorting at bus transfer hubs. Crowdsourcing passengers are willing to perform parcel delivery tasks while traveling on their bus route. When a delivery request arises, customers place their parcels at the nearest parcel temporary storage station, which could include intelligent courier lockers or retail shops near the bus stops. While waiting for their bus, passengers retrieve the parcels

from the parcel temporary storage station and carry them onto the bus. When the bus exits, the parcels are put to the temporary storage station near the bus stop. Passengers utilize these temporary storage stations as transfer hubs, facilitating parcel transfer at any bus stop within the network. Once the parcels reach the temporary storage station near the final delivery destination, customers can either collect them personally or delegate nearby crowdsourced residents for collection. Compared to the B&P mode, this delivery mode is more flexible and offers shorter delivery times.

In both the B&P and B&C modes, buses play a central role, integrating third-party delivery platforms, sorters, and crowdsourced resources—such as intelligent parcel lockers, retail stores, passengers, and residents—to facilitate the parcel delivery process. Participants in the bus system already have established travel plans. Therefore, despite the compensation for parcel delivery being relatively lower than that of dedicated delivery workers, they are willing to undertake the additional task of delivering packages during their scheduled travel[19].

To provide a more intuitive understanding of the two delivery modes, we have detailed the B&P and B&C modes based on different stages of the delivery process. Figure 2 summarizes the key components of the two delivery modes for comparative analysis.

B&P mode

1) **Delivery cycles**

   Based on the departure intervals of buses, delivery requests submitted within one departure interval are consolidated as one delivery cycle[18]. A short delivery cycle aligns with the characteristics of on-demand deliveries, featuring 'small batches, multiple batches,' which can reduce the waiting time for parcels and improve the utilization of the remaining capacity on public transport routes[13].

2) **Selection of bus terminals for bus transfer hubs**

   A bus transfer hub functions as the origin, destination, and interchange point for bus freight services. Parcels can be transferred between bus routes via these hubs. Building on the findings of Azcuy et al. we designate the terminals of bus routes as bus freight hub stations to minimize the average delivery distance for the last mile[12]. Additionally, to ensure smooth parcel transportation within the bus network, we select only bus transfer hubs that can be connected in pairs through transfers.

3) **Parcel delivery on the bus network**

   Parcel delivery on bus routes refers to the transportation of parcels by bus between the bus freight hubs corresponding to the delivery origins and destinations. The bus company is responsible for providing the schedule for each route and specifying the maximum number of parcels to be loaded. As parcels and passengers do not share storage space, the maximum number of parcels that can be loaded onto public transportation is fixed[18]. Parcels can only be dropped off and picked up at bus freight hubs throughout the transit process. The transportation routes for parcels within the bus network can be modeled as shortest path problems with capacity constraints. The path cost is determined by the transportation distance of the bus routes and is calculated using Dijkstra's algorithm[20].
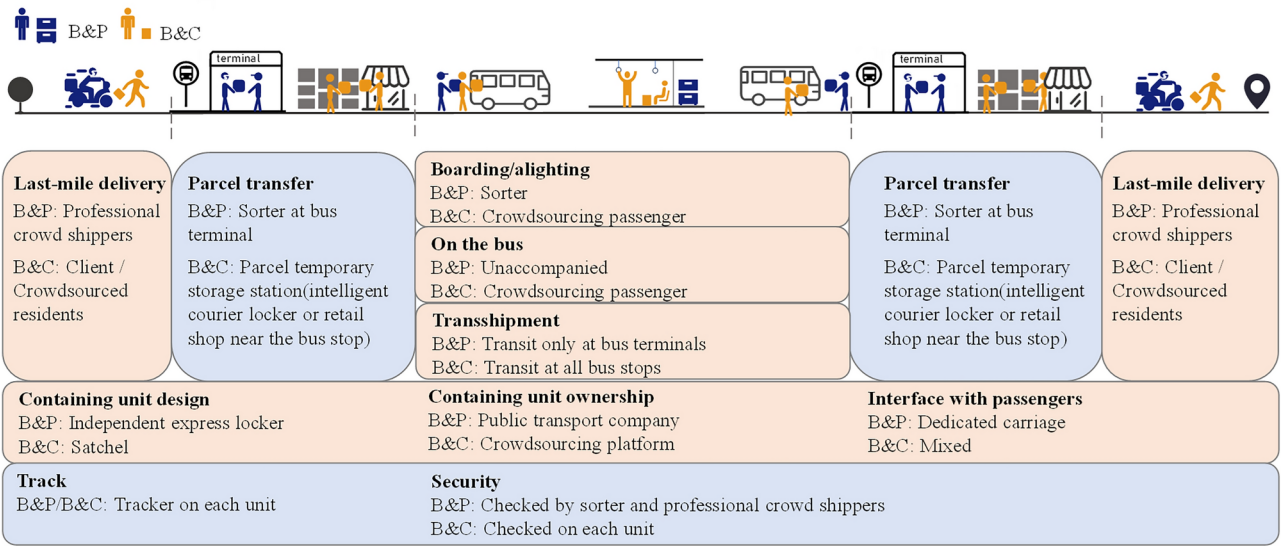

Fig. 2. Key components of B&P and B&C.

4) Last-mile delivery

Last-mile delivery refers to the transportation of parcels from a bus transfer hub to delivery origins and destinations.

- Determining the service coverage for last-mile delivery at bus transfer hubs

Given the limited number of bus transfer hubs, each hub is required to serve multiple delivery points. To determine the appropriate bus transfer hub for each delivery point, Thiessen polygons were generated for each bus transfer hub within the study area to delineate its last-mile delivery service range. Subsequently, each delivery point is assigned to its corresponding bus transfer hub based on this service range, ensuring that each delivery point is serviced by the nearest hub.

- Last-mile delivery mode

At each bus transfer hub, a professional crowd shipper is responsible for picking up and dropping off parcels to and from the corresponding delivery points of the hub. Professional crowd shippers pick up parcels from the origin, deliver them to the bus transfer hub, and transport parcels from the bus transfer hub to the delivery destination[13]. The routing problem of professional crowd shippers for end delivery can be solved by transforming it into a traveling salesman problem[21].

B&C mode

1) Delivery cycles

Like in the B&P mode, in the B&C mode, delivery requests submitted within one departure interval are consolidated into one delivery cycle based on the departure intervals of the buses.

2) Parcel transfer

- Selection of temporary parcel storage facilities for bus transfer hubs

To establish bus transfer hubs, we choose temporary parcel storage facilities located near bus stops. These facilities, referred to as parcel temporary stations, are designed for the temporary storage of parcels. Researchers often use intelligent courier lockers as temporary parcel stations due to their security and convenience. However, intelligent courier lockers are relatively expensive, starting at approximately 10,000 RMB. Drawing inspiration from some next-day delivery services that utilize retail shops for temporary storage to reduce costs and increase convenience[22], we prioritize retail shops as parcel temporary stations when they are within 30 m of bus stops. If retail shops are not available, intelligent courier lockers are used.

- Matching between bus transfer hubs and delivery points

The bus transfer hub corresponding to each delivery point is the parcel temporary storage facility that is closest to the delivery point.

3) Matching problem between parcels and crowdsourcing passengers.

The matching problem between parcels and crowdsourced passengers is presented as an instance of the multicommodity flow problem[23]. In this problem, the parcel delivery network is constructed based on passengers' travel plans. Parcels with the same origin and destination are grouped as a single type of commodity. A multi-commodity network flow model is then developed with the goal of minimizing the total delivery time.

- Sets and Indices

We define a delivery cycle based on the 15-min bus departure interval. Every 15 min, we collect parcel delivery requests and the passenger travel plans for the next 3 h. In constructing the parcel delivery network, passengers' travel plans provide the foundation. The network is represented as $G = (V, H)$, where V is the set of nodes and H is the set of links. Each link corresponds to passengers traveling between the same origin and destination bus stops. The travel time along the link is defined as the average travel time of all passengers in that segment, and the capacity of the link is determined by the total number of passengers. A represents the set of delivery requests, and delivery requests with the same origin and destination are considered as one 'commodity' k. Let K be the set of commodities, where $k \in K$, and o_k, e_k represent the origin and destination bus stops of 'commodity' k, where $o_k, e_k \in V$, The problem of matching parcels with passengers is then transformed into a multi-commodity flow network problem, with the parameters defined as follows:

- Parameters

t_{ij}: The average travel time of all passengers across link (i, j), i, j denote bus stops, and $(i, j) \in H$;

u_{ij}: Capacity of edge (i, j), equals to the number of crowdsourced passengers on link (i, j);

w_{ij}: The waiting time for commodity k at note i when delivery on edge (i, j),equal to the sum of the time the parcel waits for the passenger and the time the passenger waits for the bus;

d_k: The demand (quantity) of commodity k to be delivered.

- Decision Variables

f_{ij}^k: Flow of commodity k on edge (i, j), representing the amount of parcel k transported from i to j.

- Objective Function

The objective is to minimize the total transportation time across the network:

$$Min \sum_{k \in K} \sum_{(i,j) \in H} (t_{ij} + w_{ij}) f_{ij}^k \tag{1}$$

- Flow Conservation Constraints

These constraints ensure that the flow of each commodity k is conserved at each node (except at the source and destination nodes):

$$\sum_{j:(i,j) \in H} f_{ij}^k - \sum_{i:(j,i) \in H} f_{ij}^k = \begin{cases} d_k & \text{if } i = o_k \\ -d_k & \text{if } i = e_k \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

- Capacity Constraints

The total flow on each edge cannot exceed the edge's capacity, this constraint ensures that the transportation network does not become overloaded.

$$\sum_{k \in K} f_{ij}^k \leq u_{ij}, \forall (i, j) \in H \tag{3}$$

- Indicator Variable Constraints

$$f_{ij}^k \geq 0, \forall k \in K, (i, j) \in H \tag{4}$$

The above model is relatively simple and can be directly compiled using the YALMIP toolbox in MATLAB, calling the CPLEX solver for resolution.

4) Last-mile delivery

The current bus network is well developed; for example, in Ningbo, China, the coverage rate of bus stops reaches 78%, and the coupling degree between the service scope of bus stops and residential areas exceeds 90%. Therefore, we believe that when parcels can be delivered to the nearest bus stop via bus routes, passengers can either collect their parcels directly from the nearby parcel temporary station or hire nearby residents as crowdsourcing workers for home delivery services[24]. According to a survey on willingness to pay for home delivery services by Tobias, we set the percentage of customers who need home delivery services at 60%[25].

Definition of key performance indicators

Key Performance Indicators (KPIs) are quantifiable metrics widely employed to evaluate the performance of projects, processes, and departments. This paper aims to develop a comprehensive KPI system for assessing the implementation of on-demand delivery modes by buses. The selection of KPIs was informed by a thorough analysis of the hybrid nature of these delivery modes, with particular emphasis on their impact on both public transportation systems and delivery services. To capture these multifaceted effects, the proposed evaluation criteria are categorized into four key dimensions, inspired by the Balanced Scorecard framework—namely, delivery cost, delivery efficiency, user experience, and external impact. These dimensions are aligned with the core objectives of minimizing operational costs, enhancing efficiency, and evaluating the broader social and environmental implications of the delivery process. Furthermore, this categorization adheres to established

performance measurement frameworks in logistics and transportation management, ensuring the evaluation is grounded in widely accepted principles (Table 2).

While conventional metrics such as 'labor costs,' 'average delivery time per kilometer,' 'demand-supply ratio,' and 'electricity consumption' are extensively discussed in the existing literature, this study refines these indicators by providing more precise definitions and calculation methods specifically tailored for on-demand delivery modes[8,11,13,16]. These refinements are essential for addressing the specific challenges and operational efficiencies introduced by integrating buses into the parcel delivery process.

However, traditional KPIs do not fully account for the unique characteristics associated with the integration of bus systems into the delivery network. To address this limitation, we introduce several new KPIs, including the 'cost increase ratio of en-route destination changes,' 'infrastructure and equipment costs,' and 'total road utilization.' These indicators are specifically designed to capture the distinctive features of bus-based delivery modes, such as the necessary infrastructure modifications and the implications for road space and public transportation efficiency.

In developing this KPI system, we also considered additional potential indicators, such as customer satisfaction and system reliability. However, due to the limited availability of reliable data in the context of our study and the indirect relevance of these indicators to the operational concerns of integrating buses into the delivery process, they were not included in the final KPI set. Our focus remained on those KPIs that directly measure operational performance, cost-effectiveness, and the environmental impact of the hybrid delivery modes.

The KPIs system includes all input variables and their calculation methods, as shown in Table 3.

1) Infrastructure and equipment cost (I_1)

The infrastructure and equipment costs represent the initial investment required to establish and maintain a delivery plan. This indicator reflects the costs associated with the modifications needed in the public transportation system when buses are used for parcel delivery. The infrastructure and equipment costs of modes B&P and B&C ($I_1^{B\&P}, I_1^{B\&C}$) can be calculated using Eqs. 5 and 6.

$$I_1^{B\&P} = C_B \tag{5}$$

$$I_1^{B\&C} = C_S \tag{6}$$

2) Labor cost (I_2)

The labor cost refers to the expenses related to the payment of human resources involved in the delivery service. The labor cost is calculated by dividing the total delivery labor cost by the shortest transport distance based on the road network between the two points of delivery origin and destination (Eqs. 7 and 8). In the B&P mode, the labor costs include those incurred by the bus company, sorters, and professional crowd shippers. In the B&C mode, the labor costs involve contributions from passengers and residents acting as crowd-sourced delivery agents.

$$I_2^{B\&P} = \frac{C_c \cdot l_c + C_b \cdot (n+1)}{l} + \frac{C_a}{d} \tag{7}$$

$$I_2^{B\&C} = \frac{C_p \cdot (n+1) + C_r}{l} \tag{8}$$

3) Average delivery time per kilometer (I_3)

Category	Indicators	Variable	Unit
Delivery cost	Infrastructure and equipment cost	I_1	CNY
	Labor cost	I_2	CNY/km
Delivery efficiency	Average delivery time per kilometer	I_3	min/km
	Cost increase ratio of en-route destination changes	I_4	–
User experience	Demand–supply ratio	I_5	–
	Client's extra physical effort	I_6	km
External influence	Electricity consumption	I_7	W/km
	Total road utilization	I_8	m²/pcs

Table 2. Definition of KPIs.

Notations	Definition	Unit
A	Set of delivery demands in one day, $A = \{1, 2, 3...a\}$: Calculated based on actual data	–
l	The delivery distance of the delivery demand.: The distance of the shortest path from the origin to the destination based on the road network	km
l_c	The delivery distance of professional crowd shipper: Calculated based on the shortest path algorithm	km
l_b	The delivery distance of buses	km
l_r	The distance between the bus stop and the delivery destination	km
n	The number of bus transfers when delivery parcels	–
C_B	The cost of installing all lockers inside the buses: The cost to install a locker is 500 CNY	CNY
C_S	The cost of all temporary storage facilities: The cost to install an intelligent courier locker is 10,000 CNY, and the rental cost of a retail store is 20 CNY/day	CNY
C_c	The delivery cost by professional crowd shippers. The initial transportation fee is set at 6.4 CNY for distances up to 3 km. An additional charge of 1.8 CNY/kilometer applies for distances exceeding the initial range[26]	CNY/km
C_b	The cost of transporting parcels by bus for one trip: Assuming the space occupied by a parcel on a bus is 1/4 of the space occupied by a passenger and the bus fare for each passenger is 2 CNY[27], the cost of bus transport for a parcel is calculated to be 0.5 CNY per parcel. An additional 0.5 CNY is added for each transfer	CNY/trip
C_a	The labor cost paid to bus terminal sorting staff: 150 CNY/day per staff member with one staff member assigned to each station	CNY/day
C_p	The cost of transporting one item of parcel for passengers: 1.5 CNY /kilometer	CNY/km
C_r	The delivery cost for residents acting as crowd-sourced delivery: Delivery within 500 m is 0.5 CNY, with an increase of 0.5 CNY for each additional 500 meters[11]	CNY/km
t_b	The bus travel time: calculated from the speed of bus, bus: 25 km/h	min
t_w	Bus travel and waiting time: Calculated based on bus departure time	min
t_c	The professional crowd shipper's delivery time: Calculated from the speed of transport, electric bicycles: 20 km/h	min
t_e	The sorting time at the bus terminals: Sorting a parcel takes 3 min	min
t_p	The passenger delivery time: calculated based on Eq. (1–4)	min
t_r	The walking time from the origin/destination to the parcel temporary storage station: Calculated from the speed of transport, walk: 7 km/h	min
E_b	The electrical energy consumed by buses: A bus can transport multiple parcels, and the average single parcel consumption of electrical energy is calculated when the bus is fully loaded .A single piece of parcel consumes 4 w/km[28]	w/km
E_c	The electrical energy consumed by e-bikes: In the scenario where professional crowd shippers can consolidate deliveries, each electric bicycle transports four parcels. A single parcel consumes 50 w/km[29]	w/km
E_s	The electrical energy consumed by the intelligent courier locker: A single piece of parcel consumes 25 w/day[30]	w/km
O_b	A single parcel that takes up road width by bus: Occupation of road area of a bus is 30m^2, (according to **the Urban Road Engineering Design Code**, in China) and a single parcel takes up road space is 0.43 m	m
O_c	A single parcel that takes up road width by e-bikes: Occupation of road area of an electric bicycle is 1.158 m^2(according to **the Urban Road Engineering Design Code**, in China), and a single parcel takes up road space is 0.54 m	m

Table 3. Notation for key parameters used in the evaluation indicators.

The average delivery time per kilometer is calculated by dividing the total delivery time by the shortest transport distance between the two points of delivery origin and destination based on the road network in a specific mode. The delivery time includes transfers, transportation, and waiting time along the bus route, as well as the time required for parcel delivery between the bus station and the delivery start and end points. This metric is often used to describe the speed and efficiency of delivery service modes.

$$I_3^{B\&P} = \frac{t_b + t_w + t_c + t_e}{l} \tag{9}$$

$$I_3^{B\&C} = \frac{t_p + t_r}{l} \tag{10}$$

4) Cost increase ratio of en-route destination changes (I_4)

Cost increase ratio of en-route destination changes refers to the additional cost of time required for the system to respond promptly and accurately complete the order delivery task when the recipient needs to make changes to delivery information during the delivery process. This indicator demonstrates the extent to which the flexibility of the on-demand delivery mode is affected by the participation of public transport.

We let o and e be the origin and destination of the initial delivery, respectively, and let e' be the changed destination. We indicate the original delivery process with lp, which represents the ratio of the distance already traveled before changing the destination to the total distance between o and e. M is the position of the parcel at the time the delivery destination is changed, which is calculated by lp (Eq. 11). The cost increase ratio of en-route destination changes (I_4) is calculated with Eq. 12. t_{me} and $t_{me'}$ are the delivery times spent on d_{me} and

$d_{me'}$, respectively. Due to the different time compositions and calculation methods of t_{me} and $t_{me'}$ across different modes (Reference Eqs. 9 and 10), we use $g(x)$ to represent the calculation. The larger I_4 is, the less flexible the delivery mode is for en route destination changes.
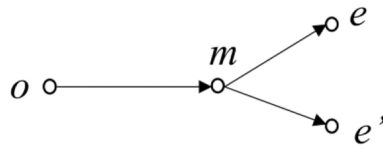
$$d_{me} = (1 - lp) \cdot d_{oe} \tag{11}$$

$$t_{me} = g(d_{me}) \tag{12}$$

$$t_{me'} = g(d_{me'}) \tag{13}$$

$$I_4^{B\&P,B\&C} = \frac{t_{me'} - t_{me}}{t_{oe}} \tag{14}$$

5) Demand–supply ratio (I_5)

The demand–supply ratio is used to measure the relationship between the demand and supply of on-demand delivery services. The demand–supply ratios of B&P and B&C are calculated according to Eqs. 15 and 16.

$$I_5^{B\&P} = \frac{a}{\sum\limits_{h=1}^{a} \min_R \{q_R(h)\}} \tag{15}$$

$$I_5^{B\&C} = \frac{a}{\sum\limits_{h=1}^{a} \min_R \{g_R(h)\}} \tag{16}$$

6) Client's extra physical effort (I_6)

The client's extra physical effort refers to the number of miles the customer has to travel to retrieve the parcel compared to door-to-door delivery. This indicator reflects the convenience of the delivery mode. In this paper, this is expressed as the average distance the customer must walk for each delivery request (Eq. 17).

$$I_6^{B\&C} = l_r \tag{17}$$

When customers choose crowdsourcing residents to help with delivery, l_r is equal to 0.

7) Electricity consumption (I_7)

The electricity consumption is the electrical energy consumed for transporting a single parcel for 1 km. This indicator reflects the environmental friendliness of the delivery system. In the B&P mode, the electrical consumption comes from buses and e-bikes. In the B&C mode, the electrical consumption comes from intelligent lockers and buses (Eqs. 18 and 19).

$$I_7^{B\&P} = \frac{E_b + E_c}{l} \tag{18}$$

$$I_7^{B\&C} = \frac{E_b + E_s}{l} \tag{19}$$

8) Total Road Utilization (I_8)

Total road utilization refers to the amount of road resources utilized during parcel delivery. This indicator reflects the road resources utilized by various on-demand delivery modes and effectively demonstrates the contribution of the bus system in reducing road occupancy. It can be calculated by multiplying the area occupied by a single package transported by the vehicle by the transportation distance of the vehicle (Eqs. 20 and 21).

$$I_8^{B\&P} = O_b \cdot l_b + O_c \cdot l_c \tag{20}$$

$$I_8^{B\&C} = O_b \cdot l_b \tag{21}$$

Case study

Basic information of the study area

To evaluate the delivery performance and applicability of the B&P and B&C modes, we conducted a case study in selected areas of downtown Ningbo, China, hereafter referred to as the "study area." The study area covers a total of 43.2 square kilometers and has a population of 217,000. It includes 288 bus routes, 142 bus stops, and 27 terminals, providing excellent public transportation facilities and favorable conditions for integrated transportation[13]. Table 4 presents detailed information about the 288 bus routes in the study area.

Based on Meituan's criteria for choosing retail stores as pick-up points in China, we selected 58 retail stores located within 60 m of a bus stop as temporary pick-up points for the B&C delivery mode. For the remaining 84 bus stops, we used automated parcel lockers for temporary parcel storage. The distribution of these facilities is illustrated in Fig. 3.

We used the built-in tools of the ArcGIS platform to draw the Thiessen polygons. Each bus terminal station (or bus stop) was treated as a node, and the study area was divided using the Thiessen polygon algorithm to define service areas for each bus terminal station (or bus stop). The resulting polygons represent areas where all points are closer to a given bus stop than to any other stop. Bus terminal stations and bus stops serve as key transfer hub for on-demand delivery, with their service areas defined using Voronoi diagrams, as shown in Fig. 4.

Drawing from previous work on the generation of on-demand delivery requests[31], we used the spatial distribution of residential POIs to determine the spatial distribution of delivery demand endpoints. According to Shen et al. the temporal distribution of delivery demand in the research area was distributed proportionally over time[32]. Finally, we obtained the overall number of on-demand delivery requests and their corresponding spatial distribution (Fig. 5).

Calculation and analysis of KPIs for each delivery mode

We used the B&P and B&C modes to meet the 18,349 delivery demands in the study area and summarized their average results in each KPI. We also compared the evaluation results of the two modes with those of the third-party platform delivery (P) mode (Table 5) and plotted the radar chart (Fig. 6).

Overall, compared to traditional delivery modes, both the B&P and B&C modes can effectively decrease labor costs (I_2), electricity consumption (I_7) and total road utilization (I_8) due to the low compensation for participants, minimal energy consumption, and reduced negative external impacts in the bus transportation system. However, implementing B&P and B&C requires modifications to facilities and equipment in the public transportation system, increasing infrastructure and equipment costs (I_1). Additionally, constraints imposed by bus routes will result in increased delivery time (I_3) and time required to change orders (I_4).

Compared to the B&P mode, the B&C mode has advantages in terms of labor cost(I_2)delivery efficiency (I_3,I_4) and external influence (I_7, I_8) .In the B&C mode, since the compensation cost for passenger is much lower than that for traditional third-party delivery, the labor costs in the B&C mode are lower than those in the B&P mode. Additionally, parcels can be transferred at any bus station, making the mode more flexible while also resulting in shorter average delivery distances. However, the infrastructure and equipment cost (I_1) in the B&P mode are lower than those in the B&C mode, as the cost of installing sellers on buses is lower than that

	Unit of measure	Regular bus routes	Microcirculatory bus routes
Proportion	%	73	27
Average length of bus route	km	23.5 km	9.75 km
Rated passenger capacity	people	50	35
Average carrying capacity per trip	people	34	25
Departure interval	min	5–15	10–25
Residual capacity of the vehicle	people	16	10
Average fare	CNY per person	2.13	1.52

Table 4. Information on the bus routes.

Fig. 3. Basic information of the study area.

（a）　Service coverage of bus terminals
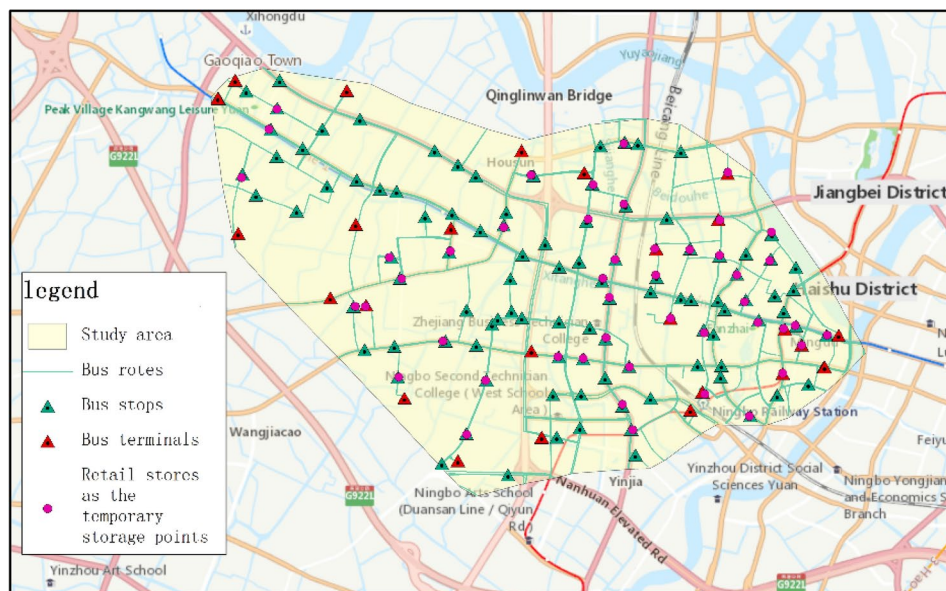
(b)　Service coverage of bus stops
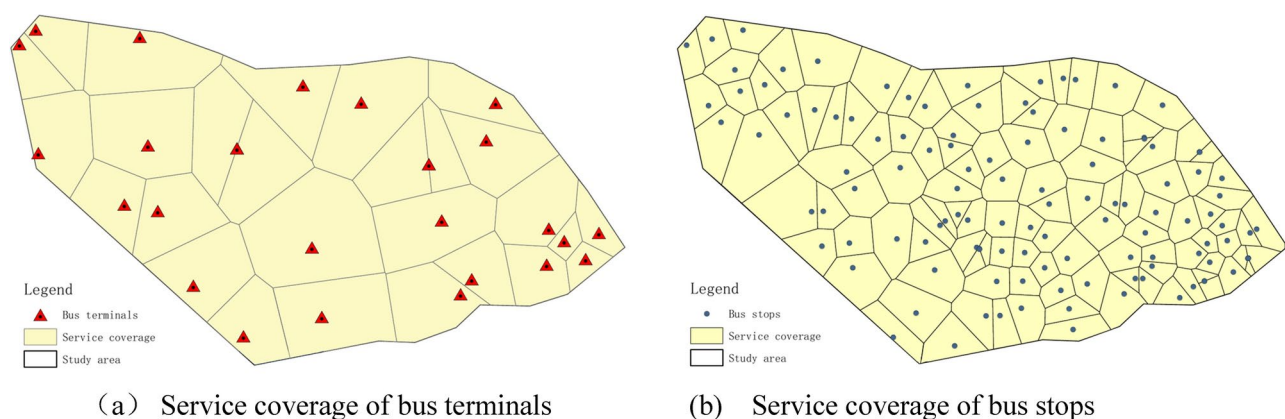
Fig. 4. Service coverage for last-mile delivery of bus stops and bus terminals.

of installing intelligent courier lockers. Additionally, the B&P mode allows for door-to-door transportation, eliminating the client's extra physical effort (I_6).

Next, we compare and analyze various delivery modes from the perspective of each indicator.

1) Infrastructure and equipment cost (I_1)

The B&C mode incurs the highest infrastructure and equipment costs due to the need to construct intelligent courier lockers near bus stops, and the quantity of construction required is substantial. However, in later stages, if the parcel storage volume at bus stops is small or during low-demand periods, intelligent courier lockers can be rented to other logistics companies to store parcels, generating additional revenue to offset the high infrastructure and equipment costs. The initial construction cost of the B&P mode involves installing sorters on buses. Since sorters on buses are much less expensive than intelligent courier lockers, the infrastructure and equipment costs of the B&P mode are also relatively lower. The infrastructure and equipment costs of the P mode are the lowest, at 0. This is because the entire delivery task in the P mode is carried out by dedicated crowdsourced couriers who use their own vehicles for the delivery process.

2) Labor cost (I_2)

Overall, the average delivery costs of B&P and B&C are reduced by as much as 28.3% and 51%, respectively, compared to those of P. This indicates that the involvement of buses in on-demand delivery can effectively reduce the cost. Table 6 provides the compensation earned by each participant for completing delivery tasks in each mode.
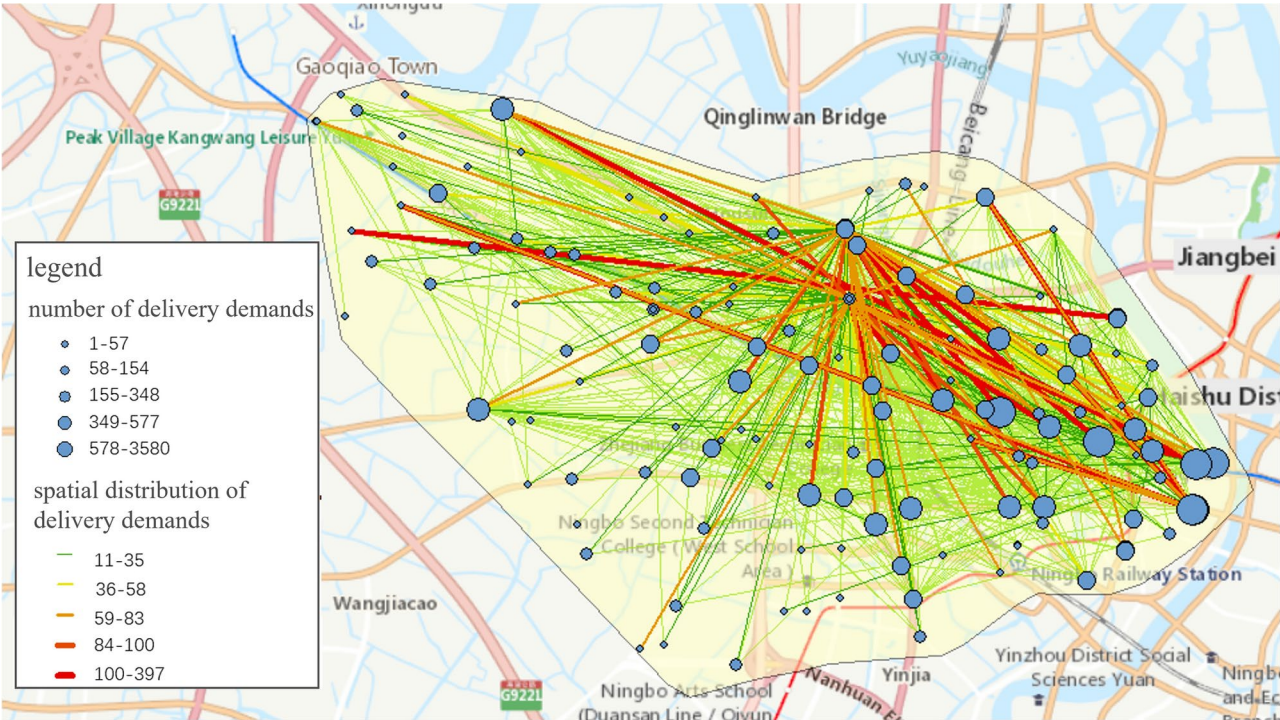
Fig. 5. Daily on-demand delivery requests in spatial distribution.

Indicator	Variable	B&P (Compared to P)	B&C (Compared to P)	P
Infrastructure and equipment cost	I_1(CNY)	105,000	581,160	0
Labor cost	I_2(CNY /km)	2.3 (-28.3%)	1.56 (-51%)	3.21
Average delivery time per kilometer	I_3(min)	23.9 (4.1times)	6.5(1.1times)	5.8
Cost increase ratio of en-route destination changes	I_4	57.93% (3.3 times)	28% (1.6 times)	17.51%
Demand–supply ratio	I_5	0.306 (-69%)	0.613 (-39%)	1
Client's extra physical effort	I_6(km)	0	0.11	0
Electricity consumption	I_7(W/km)	29 (-85%)	2.15 (-99%)	200
Total road utilization	I_8(m²/pcs)	1066 (-56%)	517 (-79%)	2455

Table 5. Calculation results of the KPIs.

Table 6 illustrates that the lower labor costs in the B&P mode are due to the bus system's ability to efficiently consolidate parcel flows, thereby reducing the need to hire third-party couriers. Although the B&P mode incurs additional costs for sorters and bus delivery, the overall cost remains relatively low. The cost reduction in the B&C mode is attributed to the use of passengers for on-demand deliveries. Since both passengers and buses are already operating based on their existing travel plans, the delivery tasks are carried out as an add-on, avoiding the need to pay the higher costs like third-party couriers.

3)   Average delivery time per kilometer (I_3)

The overall average delivery time per kilometer for the B&P mode is greater than that for the B&C and P modes. In the B&P mode, parcels can only be loaded and unloaded at the bus terminal. As a result, parcels must travel a longer distance on the bus route, leading to longer delivery times in the B&P mode. However, to ensure the comparability of the indicator when calculating the average delivery time per kilometer, we use the shortest road distance between the origin and destination of the delivery demand.

As shown in Fig. 7, both B&P and B&C experience an increase in average delivery time per kilometer as the delivery distance increases, like P. The average delivery time per kilometer for B&C is comparable to that of the P mode. Moreover, when the delivery distance exceeds 2.93 km, the average delivery time of the B&C mode is lower than that of the P mode. This suggests that for medium and long distances, B&C has an advantage in terms of delivery time. The B&P mode shows larger overall fluctuations, mainly due to the transportation route of parcels in the B&P mode. When the nonlinear coefficient of the parcel transportation route on the bus network is
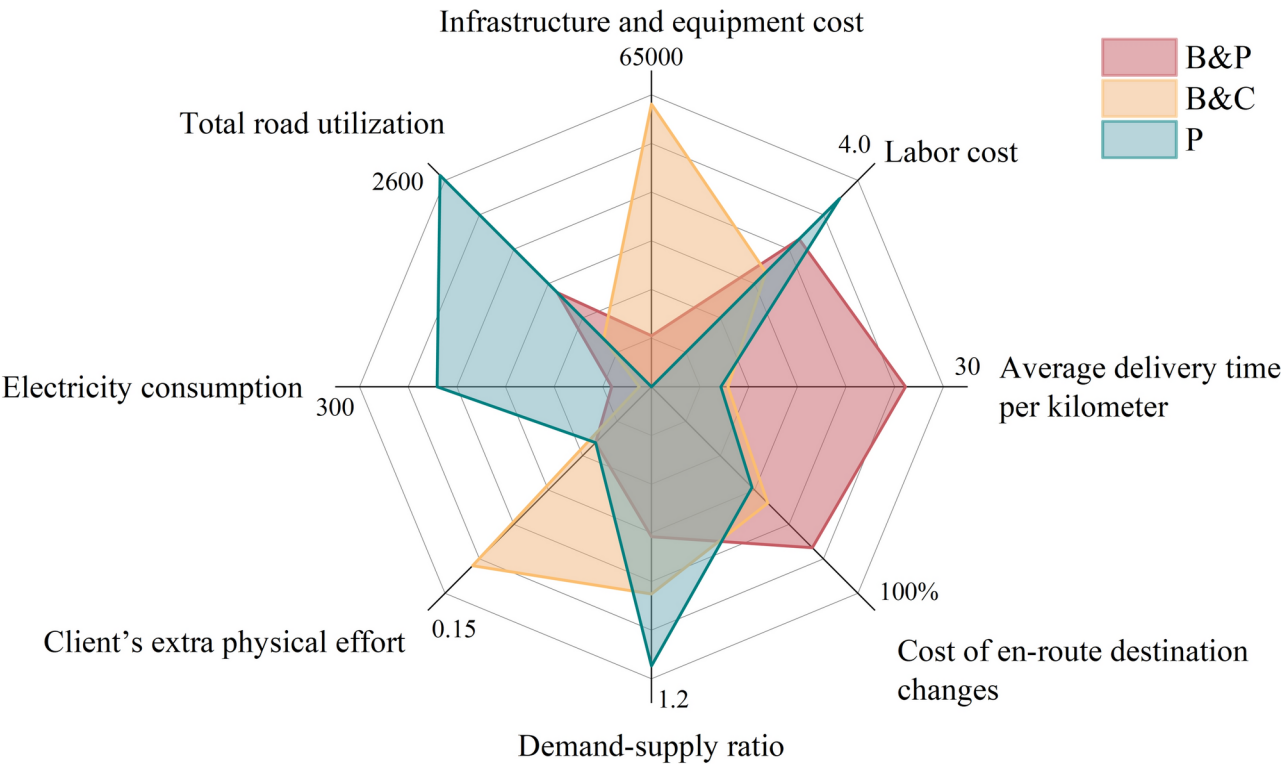
Fig. 6. Radar chart of delivery modes.

Mode	B&P mode			B&C mode		P mode
Participants	**Professional crowd shipper**	**Bus company**	**Sorter**	**Passengers**	**Residents**	**Professional crowd shipper**
Compensation per delivery	6.4 CNY (first 3 km), 1.8 CNY/km thereafter (Combined delivery for multiple orders)	0.5 CNY per order, + 0.5 CNY per transfer	150 CNY/day/person, 27 people total	1.5 CNY /person	0.5 CNY /km	6.4 CNY (first 3 km), 1.8 CNY/ km thereafter (Individual deliveries per order)
Labor costs Required per Day	64,336 CNY	21,101 CNY	4050 CNY	55,047 CNY	5435 CNY	124,979 CNY
Total daily labor costs per mode	89,487 CNY			60,482 CNY		124,979 CNY
Average labor cost	2.3 CNY /km			1.56 CNY /km		3.21 CNY /km

Table 6. Labor cost distribution across different delivery modes.

small and there is no need for transfers, the delivery time is relatively short. However, if the nonlinear coefficient is large, the delivery time will increase.

Although the overall average delivery time per kilometer for B&P is relatively long, we found that for specific demands circled in red in Fig. 7, B&P showed the shortest average delivery time. We identified the spatial locations of these on-demand delivery demands and noted favorable performance metrics when fulfilled by the B&P mode, including low labor costs (0.32 CNY/km), short average delivery time per kilometer (6 min/km), and minimal electricity consumption (7.81 km/W). By analyzing their spatial distribution (see Fig. 8), we observed that the delivery routes within the bus network tend to have minimal turns or detours, with a nonlinear coefficient of less than 1.7. We refer to these delivery requests as optimal delivery scenarios for B&P. In such scenarios, utilizing the public transportation network for delivery eliminates the need for transfers, thereby reducing delivery time and distance.

To further investigate the applicability of these optimal delivery scenarios for B&P, we expanded our study to encompass the entire city of Ningbo. We identified bus terminals along bus routes with nonlinear coefficients less than 1.7 and transport speeds of at least 20 km/h. The areas within 500 m around these terminals were designated optimal service areas for the B&P mode (see Fig. 9). Additionally, we collected location data for key sites with on-demand delivery demands, such as large supermarkets and logistics hubs. Our analysis revealed that the optimal service areas encompass a significant portion of these sites, including 32% of large supermarkets and 36% of logistics hubs. This indicates that retail establishments and logistics firms can leverage the B&P mode as a supplementary option for on-demand delivery, potentially reducing costs while maintaining delivery speed and service quality.
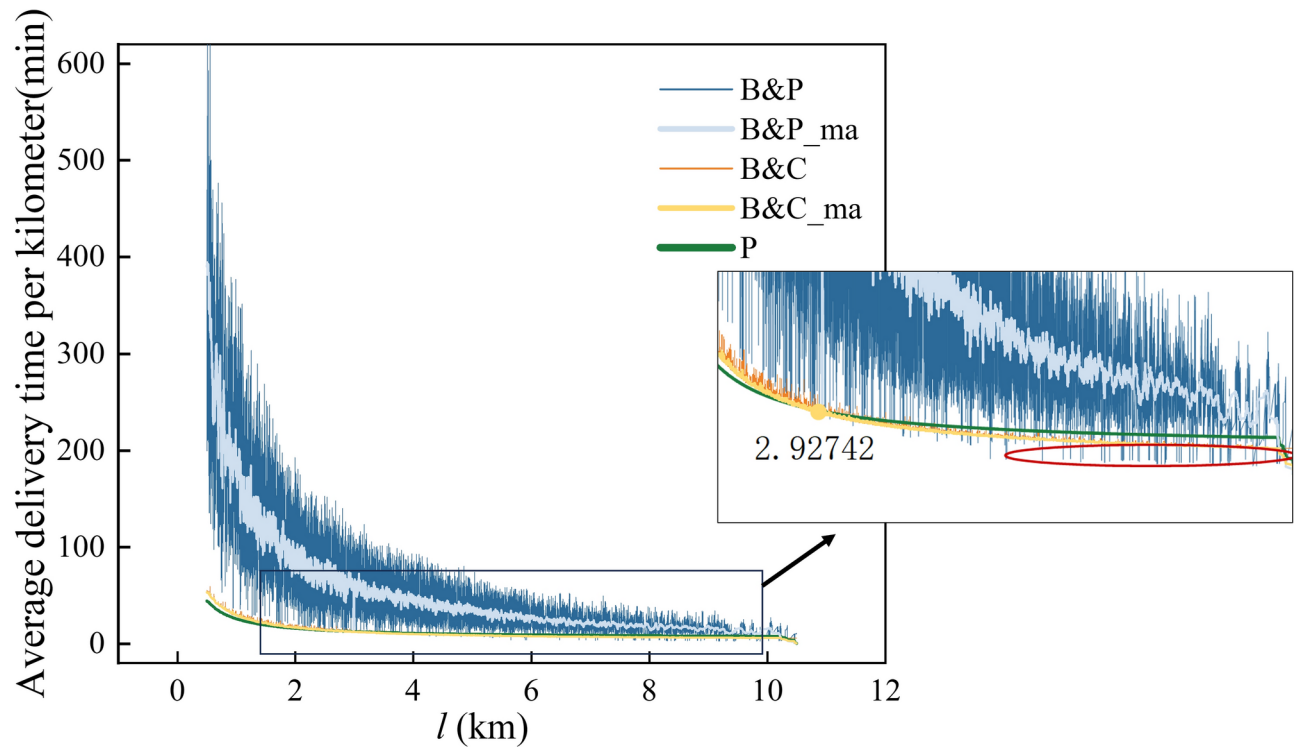
Fig. 7. Average delivery time per kilometer for different delivery modes at various delivery distances.
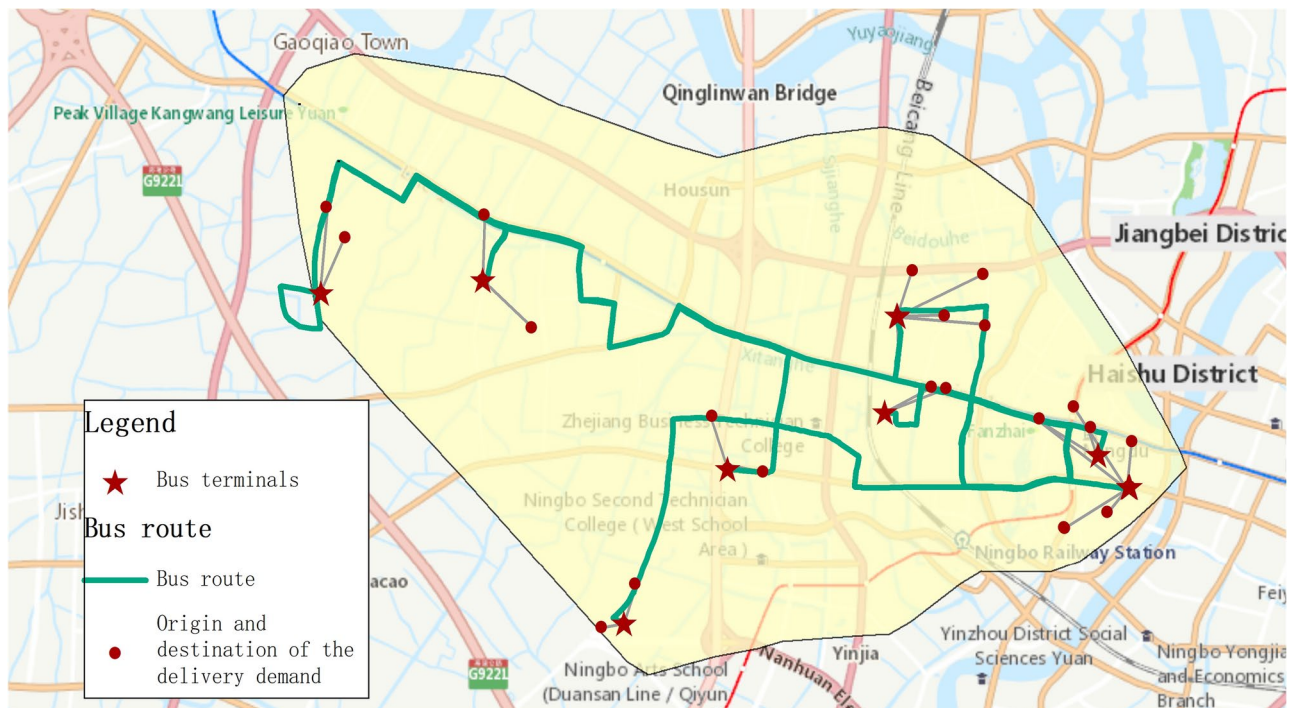

Fig. 8. The locations of special scenarios suitable for the B&P mode.

4) Cost increase ratio of en-route destination changes (I_4)

We randomly selected 100 delivery demands and changed the delivery destination at different points in the delivery process (when 25%, 50%, 75%, and 100% of the original delivery route (lp) was completed) to explore
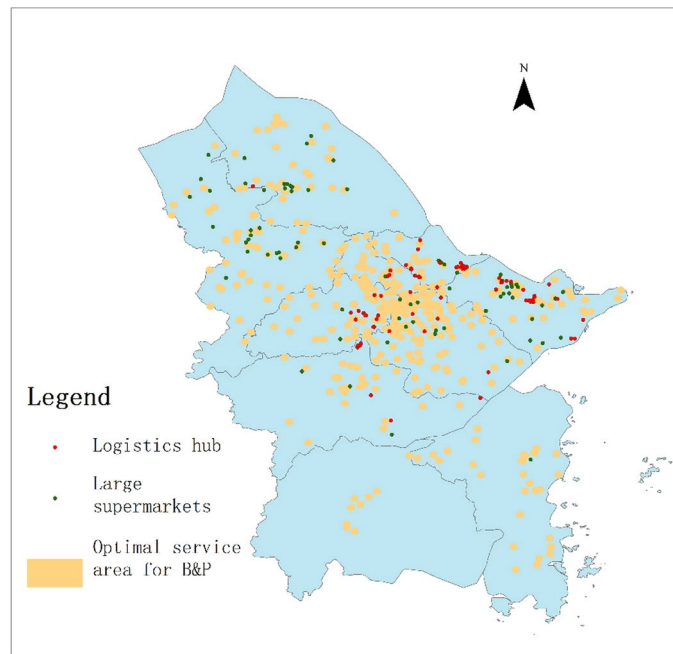
Fig. 9. Distribution of optimal service areas.
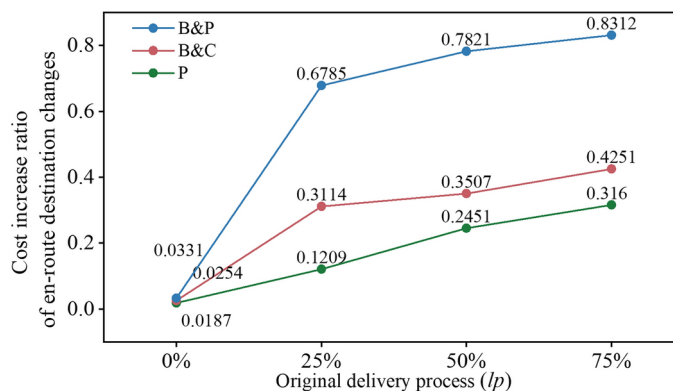
Fig. 10. Cost increase ratio of en-route destination changes for B&P, B&C and P.

the cost increase ratio of en-route destination changes across the three delivery modes: B&P (Bus & Parcel), B&C (Bus & Collection), and P (Parcel only) (Fig. 10).

The results show that the cost of changing delivery destinations increases as the delivery progresses. This is because the further along the delivery route, the more effort and resources are required to reroute the package. In comparison, both B&P and B&C modes are less flexible than the P mode, which is free from bus routes and can adjust delivery paths more easily. The B&P and B&C modes are tied to bus routes, making it harder to adjust the delivery destination once the delivery is underway. Additionally, the B&P mode is less flexible than the B&C mode. This is because, in the B&P mode, packages can only be transferred at the starting and final bus stops, limiting the potential for adjusting delivery routes. In contrast, the B&C mode offers more flexibility as it allows parcels to be transferred at multiple points along the bus route. In summary, the B&P and B&C modes face more challenges in altering delivery destinations en-route compared to the P mode, which can change direction more easily at any time. This highlights the lower delivery flexibility of the B&P and B&C modes due to their reliance on bus routes.

5) Demand–supply ratio (I_5)

From the perspective of the demand and supply of on-demand delivery within a day, both B&P and B&C have a demand–supply ratio lower than 1, indicating that B&P and B&C can meet the delivery demand of on-demand delivery.

To further explore the supply and demand situation during different time periods, we calculated the demand–supply ratio for the B&P and B&C modes from 4:00 to 22:00 (Fig. 11(a)) based on the hourly demand for on-demand delivery and the delivery capacity that the B&P and B&C modes could provide (Fig. 11(b)). The results show that before 19:00, both modes can satisfy the delivery demand. However, after 20:00 for B&P and after 19:00 for B&C, due to a decrease in public transportation capacity and high on-demand delivery demand, the delivery supply falls short of demand.

6) Client's extra physical effort (I_6)

Since the last-mile delivery for both the P and B&P modes is door-to-door delivery, clients do not need to expend extra physical effort. Extra physical effort is required for the B&C mode. According to the calculation results, clients on average need to expend 0.11 km of physical labor, which means that on average, customers need to walk 0.11 km per order to pick up parcels. The walking distance is within the acceptable range for customers[33].

7) Electricity consumption (I_7)

Overall, B&P and B&C achieved 85% and 99% lower electricity consumption than P, respectively, mainly due to the lower electricity consumption when using buses for freight transport. However, the electricity consumption of B&P is greater than that of B&C due to the greater distance traveled by buses.

Figure 12 shows that the electricity consumption of B&C and P is relatively stable, while that of B&P still fluctuates significantly. Nevertheless, as the minimum transportation distance increases, the energy consumption of the B&P decreases and tends to stabilize. When the distribution demand is greater than 8 km, the electricity consumption of B&P is close to that of B&C and stabilizes at approximately 12 km/watt.

8) Total road utilization (I_8)

According to Table 4, B&C utilizes the least amount of road space, with a reduction of 79% compared to P. Similarly, B&P also demonstrates lower road utilization, showing a decrease of 56% compared to P. This disparity is attributed to the inherent advantages of buses, which lead to reduced road usage by B&C and B&P. However, B&P still consumes relatively more road resources due to the longer transportation distances covered by bus routes.

Sensitivity analysis of delivery demand volume

To investigate the reliability of our evaluation results, we adjusted the demand for on-demand delivery by ± 10% and ± 20% while keeping other parameters, such as the distribution of on-demand deliveries, remaining bus capacity, and transportation routes, unchanged. We then computed evaluation metrics for each on-demand delivery mode and analyzed their sensitivity to changes in on-demand delivery requests. The results are presented in Fig. 13.

According to Fig. 13, as delivery demand increases, there is a general downward trend in labor costs for the three delivery modes. This downward trend is due to the increase in delivery volume, and it becomes easier to achieve consolidated delivery, thereby reducing labor costs. In terms of the average delivery time per kilometer, the B&P delivery mode displayed a fluctuating trend. This fluctuation phenomenon is attributed to the significant fluctuations in the length of the delivery route utilized by the B&P mode for origin and destination at identical straight-line distances in different geographic locations. The overall fluctuations in electricity consumption and
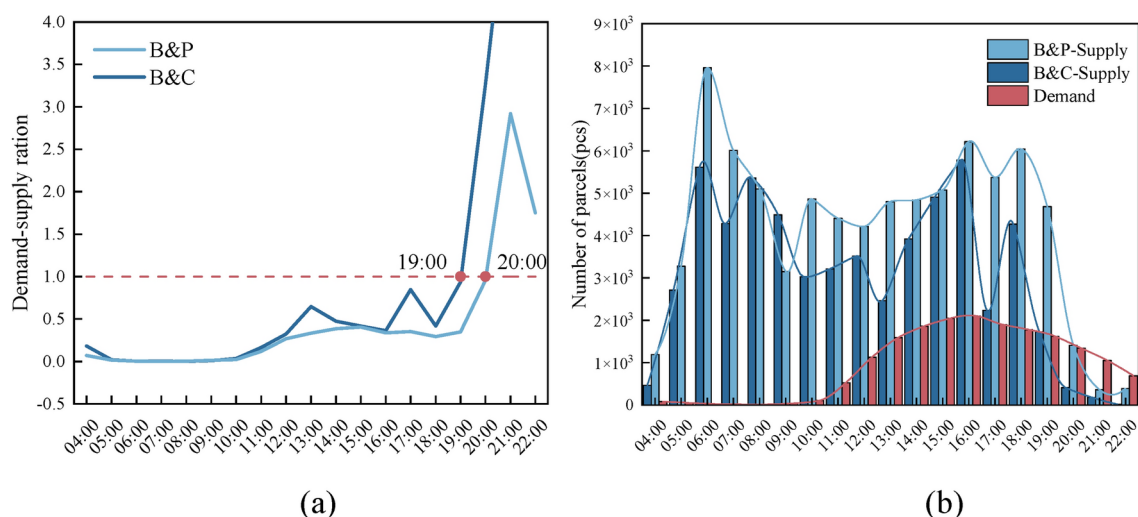

(a)　　　　　　　　　　　　　　(b)

Fig. 11. (a) Demand–supply ratio for each hour; (b) Supply and demand quantity for on-demand delivery of parcels.
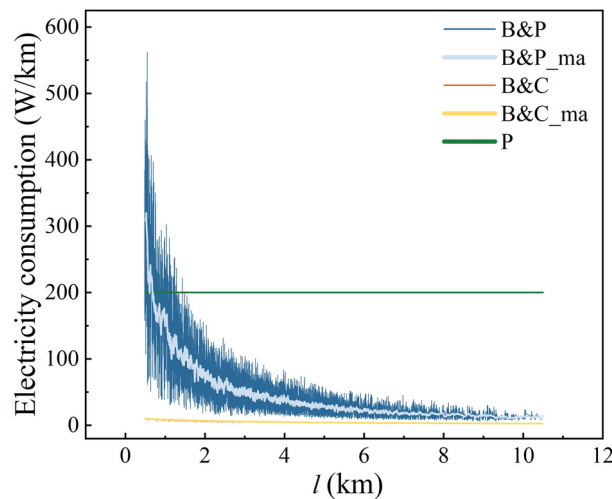
Fig. 12. Electricity consumption of different delivery modes at various delivery distances.
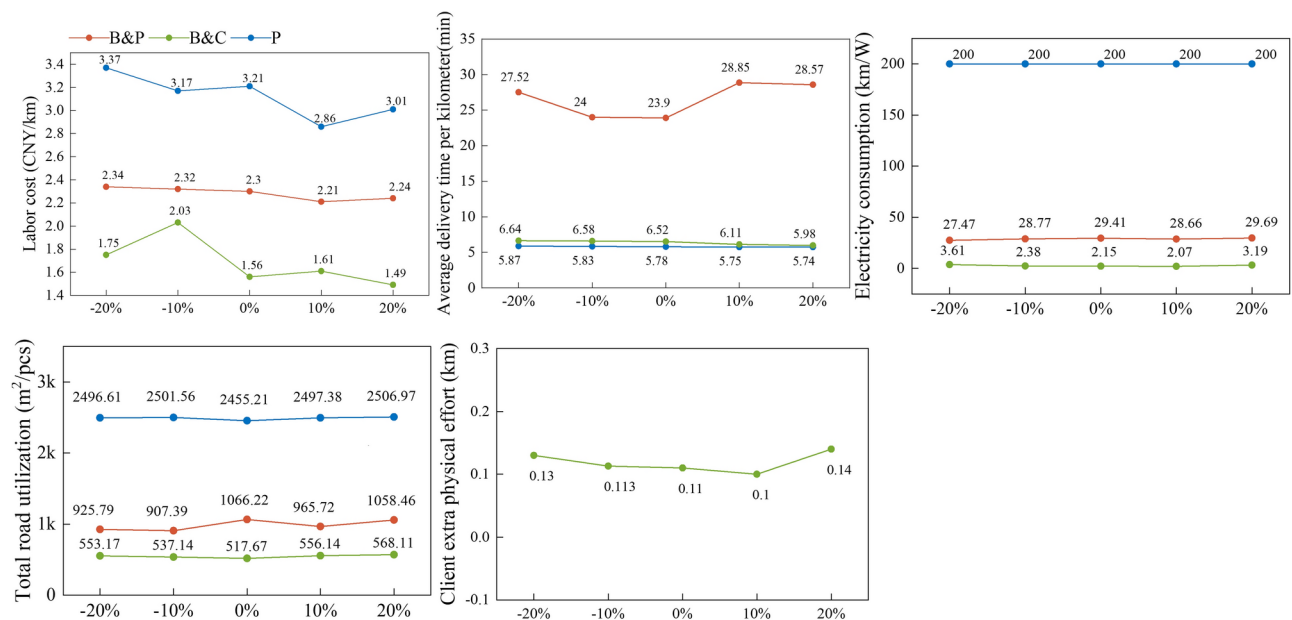

Fig. 13. Sensitivity analysis of the evaluation indicators for each delivery mode.

the road utilization rate are smaller. Additionally, for the B&C delivery mode, the additional physical effort required by customers is relatively stable.

Overall, while the various indices exhibit certain variability at different levels of on-demand delivery demands, the overall quantity variation in the relationship is not substantial. This finding suggests that our evaluation results are reliable and support the validity of the proposed approach.

Discussion
SWOT analysis
Using the KPIs introduced earlier, we conducted a comprehensive and in-depth analysis of the proposed B&P and B&C delivery modes. SWOT is an analytical technique used to qualitatively assess the strengths, weaknesses, opportunities, and threats of a studied object based on facts and opinions. A SWOT matrix was constructed for the B&P and B&C modes based on the evaluation results of these two modes, as shown in Fig. 14.

1) Strengths

Buses offer advantages in terms of energy consumption and their impact on traffic. This makes it possible for the B&P and B&C modes to have minimal negative externalities on traffic and low energy consumption. Utilizing buses for a portion of delivery tasks can also effectively reduce transportation costs. Moreover, the
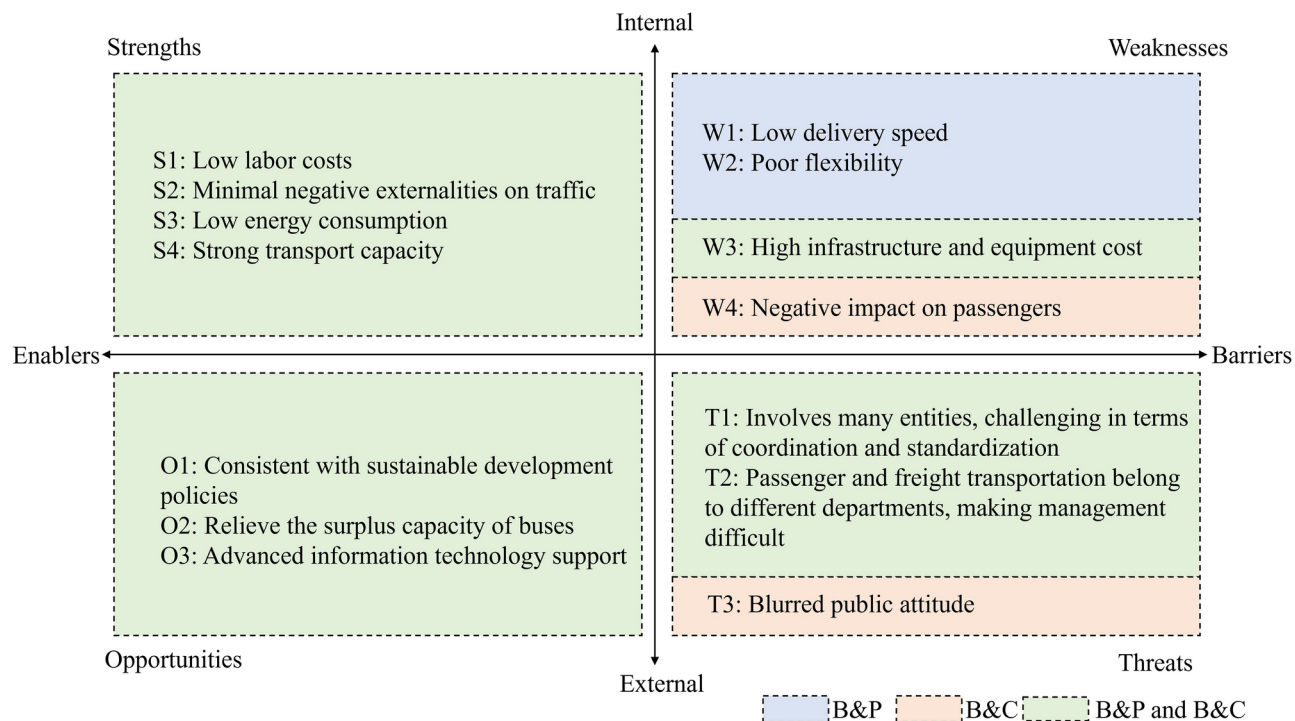
Fig. 14. SWOT analytic matrix of the B&P and B&C modes.

B&P and B&C modes have good delivery capacity and can meet most of the delivery demand volume during most times.

2) Weaknesses

The transformation of the passenger transportation system results in high infrastructure and equipment costs for both the B&P and B&C modes. Additionally, the B&P mode is more restricted by the limitations of public transportation routes, resulting in significant weaknesses in terms of delivery speed and flexibility. The B&C mode's shared storage space for parcels and passengers may also negatively impact passenger experience during parcel delivery.

3) Opportunities

The B&P and B&C modes align with current policy trends toward sustainable development, making them strong candidates for government-backed initiatives or subsidies aimed at reducing carbon emissions and improving urban mobility. Additionally, these models address the issue of surplus bus capacity, enhancing overall resource utilization. Specific policies or regulations, such as tax incentives for businesses adopting green transportation solutions, or public funding for infrastructure development, could facilitate the broader adoption of these models. Moreover, advancements in information technology enhance the coordination and real-time sharing of data between parcels, passengers, and buses, opening further opportunities for market penetration and operational optimization.

4) Threats

One significant challenge facing the B&P and B&C modes is the complexity of coordinating parcel delivery within a public transportation framework. In particular, the B&C mode faces the potential risk of low public participation and engagement, as it relies on crowdsourced passengers for parcel delivery. This introduces concerns around privacy, as passengers may need to handle personal information related to deliveries. Additionally, the risk of parcel damage or loss increases when non-professional couriers, such as passengers, are involved in the process. Regulatory frameworks ensuring passenger accountability and parcel insurance would be necessary to mitigate these risks. Furthermore, without sufficient public participation, the effectiveness of the B&C mode could be significantly reduced, posing a threat to its long-term viability.

In addition, compared to other integrated passenger and freight delivery modes, the integrated passenger and freight transportation mode involving buses has the following advantages: 1) Reduced labor costs. Unlike Cheng et al.'s combination of public transportation and truck delivery, which increases costs[34]. 2) Reducing the negative

external impacts of transportation caused by the excessive use of e-bikes, as a form of green transportation, buses have characteristics such as low energy consumption and low road space requirements. Using buses to perform some transportation tasks can effectively alleviate the negative external effects of on-demand delivery services. 3) Increasing people's willingness to participate in crowdsourced delivery. Bus stops are usually located near densely populated areas. Compared to passengers who rely primarily on taxis and subways, those who rely on buses have a lower perceived value of time. They are more willing to participate as crowd shippers for the purpose of transporting goods[4]. In terms of the size of the crowdsourced workforce, the on-demand delivery mode involving public transportation is superior to the use of taxis[35] or metros for on-demand delivery.

Application scenario analysis

Overall, both B&P and B&C have absolute advantages over the P mode in terms of labor cost and external influence. Although the relative advantages of B&P and B&C in terms of delivery efficiency and user experience are not significant, they can still narrow the gap with the P mode in certain scenarios. Therefore, we can identify these scenarios and promote B&P and B&C modes.

For the B&P mode, when the bus terminals and the bus networks consisting of these stations are relatively dense, parcels are more easily transported directly or with only one transfer, and the average delivery time per kilometer is only 6 min, achieving a delivery speed comparable to that of the P mode. As city buses gradually extend their services from railway stations to residential areas, the number of buses with shorter routes will continue to increase, and the delivery network based on terminal stations will become denser[36]. Therefore, an increasing number of scenarios will be suitable for the B&P mode. Considering the cost factors, we believe that the B&P mode is particularly suitable for scenarios where the demand points are within 1 km of the terminals and the length of the bus path based on the terminal network is less than 1.7 times the shortest path on the conventional road network.

B&C relies on an established public transportation system and takes advantage of the widespread distribution, high accessibility, low resource usage, and green nature of public transportation to achieve a low labor cost, low energy consumption, and low road-area utilization of on-demand deliveries. Although the B&C mode may be slightly less flexible and slower than the P mode, its advantages in terms of delivery time gradually become more evident as the delivery distance increases. Therefore, we believe that the B&C delivery mode is suitable for medium- to long-distance (3–10 km) on-demand delivery requests, particularly in areas and time periods where delivery scenarios are concentrated, delivery points are dense, traffic congestion is high, or environmental requirements are stringent. In the future, relevant departments can use B&P and B&C modes in appropriate scenarios to alleviate the problems of the current on-demand delivery mode in terms of cost and transportation. The specific implementation suggestions are as follows:

1) Start with a small-scale pilot and gradually expand to become the main delivery mode of on-demand delivery. The B&P mode can first be piloted in the delivery scenario of same-city logistics and then gradually developed into medium- and long-distance on-demand delivery areas. In addition, since the initial investment of the B&P mode is relatively small, it can also be used as a pioneer to develop the on-demand delivery market in urban and rural areas. B&C can first be developed at the center of urban areas with high demand for express delivery and dense bus line networks, mainly serving medium- and long-distance express delivery, and then continuously adjusted and optimized to become the main delivery mode of express delivery on this basis.
2) By taking advantage of the low labor cost, the integrated passenger and freight transportation tariffs can be freely adjusted. This will not only meet the market demand while improving B&P and B&C transportation tariffs but also promote the healthy development of integrated passenger and cargo transportation enterprises and facilitate the implementation of their operational conversion value.
3) Establish a special regulatory authority for B&P and B&C. To ensure the coordinated and efficient development of the integrated passenger and freight transportation sector, a new regulatory authority should be established to regulate the safety, quality and service aspects of immediate distribution and other integrated passenger and freight transportation sectors.

Conclusion

This paper proposes two on-demand delivery modes B&P and B&C, which involve the deep participation of bus passengers to address the negative externalities caused by third party delivery services. Comprehensive KPIs are established, and a comparison is made with traditional crowd shipping by third-party platforms to analyze the performance and applicability of the two modes. The results show that, compared to the traditional mode, B&P and B&C effectively reduce delivery labor costs and external influence, especially for mid-to-long distances. Although their relative advantages in terms of delivery efficiency and service quality are not significant, they still have broad prospects for application in specific scenarios. Finally, development recommendations were proposed for the B&P and B&C modes based on their respective applicable conditions.

While B&P demonstrates optimal delivery scenarios, it exhibits significant volatility when considered as a whole. For large-scale implementation in the future, the expansion of bus transfer hubs is essential. Currently, parcel loading, unloading, and transfers are limited to the terminals corresponding to the bus routes used for parcel transport. For example, when bus route #1 transports parcels, parcels can only be loaded and unloaded at the terminals of route #1 and cannot be handled at intermediate stops, which are the terminals of other bus routes (such as route #2), even though the terminals of bus route #2 pass through bus route #1. Future research could focus on more precise real-time parcel route matching to connect all terminals, employ faster loading and unloading technologies (such as automated machinery), and enhance the efficiency of parcel transfers at intermediate stops. This would transform all terminals into nodes for potential route changes, reducing the

nonlinear coefficient in the B&P mode and ultimately improving delivery efficiency to better meet the high real-time requirements of the on-demand delivery modes.

In addition, due to the difficulty of quantitative analysis of information leakage and parcel security issues, we did not consider these two points in the indicator setting process. However, ensuring personal privacy and good safety during crowdsourced delivery is an issue worth considering. Similar to other crowdsourced delivery modes, the involvement of non-professional couriers in crowdsourced delivery through passenger may lead to issues related to transportation safety, such as privacy breaches, parcel damage, or loss[37]. To address concerns related to personal privacy and goods safety during crowdsourced delivery, platforms need to establish clear service agreements and transaction rules, define the responsibilities of all parties involved, intensify regulatory efforts, and ensure that customer rights are protected.

This study provides a foundation for understanding the benefits and limitations of the B&P and B&C modes, several areas require further investigation. Future research could explore:

1) Dynamic Routing and Scheduling: Investigating advanced algorithms, such as real-time dynamic routing, to improve the flexibility and efficiency of the B&P mode.
2) Passenger Experience and Acceptance: Conducting empirical studies to understand passenger perspectives on sharing public transportation with parcel delivery services and examining the potential impacts on passenger satisfaction.
3) Policy and Infrastructure Development: Analyzing the role of government policies, such as tax incentives and public funding, in supporting the large-scale adoption of these delivery modes, as well as investigating the necessary infrastructure enhancements.

Data availability
The datasets used and analysed during the current study available from the corresponding author on reasonable request.

References
1. Jin, M., Li, G. & Cheng, T. C. E. Buy online and pick up in-store: Design of the service area. *Eur. J. Oper. Res.* **268**, 613–623 (2018).
2. Buldeo Rai, H., Verlinde, S., Merckx, J. & Macharis, C. Can the Crowd Deliver? *Analysis of Crowd Logistics' Types and Stakeholder Support: Towards Sustainable and Liveable Cities*. pp 89–108 (2018). https://doi.org/10.1002/9781119425472.ch5.
3. Ghaderi, H., Zhang, L., Tsai, P.-W. & Woo, J. Crowdsourced last-mile delivery with parcel lockers. *Int. J. Prod. Econ.* **251**, 108549 (2022).
4. Mazzarino, M. & Rubini, L. Smart urban planning: evaluating urban logistics performance of innovative solutions and sustainable policies in the Venice lagoon—the results of a case study. *Sustainability* **11**, 4580 (2019).
5. Pereira, R. H. M. Future accessibility impacts of transport policy scenarios: equity and sensitivity to travel time thresholds for bus rapid transit expansion in Rio de Janeiro. *SSRN Scholarly Paper at* https://doi.org/10.2139/ssrn.3147748 (2018).
6. Wyrowski, A., Boysen, N., Briskorn, D. & Schwerdfeger, S. Public transport crowdshipping: moving shipments among parcel lockers located at public transport stations. *Spectr.* https://doi.org/10.1007/s00291-024-00748-0 (2024).
7. Elbert, R. & Rentschler, J. Freight on urban public transportation: A systematic literature review. *Res. Transp. Bus. Manag.* **45**, 100679 (2022).
8. Cheng, G., Guo, D., Shi, J. & Qin, Y. Smart city-wide package distribution using crowdsourced public transportation systems. *IEEE Internet Things J.* **6**, 7584–7594 (2019).
9. Mourad, A., Puchinger, J. & Van Woensel, T. Integrating autonomous delivery service into a passenger transportation system. *Int. J. Prod. Res.* **59**, 2116–2139 (2021).
10. Pimentel, C. & Alvelos, F. Integrated urban freight logistics combining passenger and freight flows – mathematical model proposal. *Transp. Res. Proc.* **30**, 80–89 (2018).
11. Zhang, M., Cheah, L. & Courcoubetis, C. Exploring the potential impact of crowdshipping using public transport in Singapore. *Transp. Res. Rec.* **2677**, 173–189 (2023).
12. Azcuy, I., Agatz, N. & Giesen, R. Designing integrated urban delivery systems using public transport. *Transp. Res. Part E Logist. Transp. Rev.* **156**, 102525 (2021).
13. Machado, B., de Sousa, A. & Pimentel, C. Operational planning of integrated urban freight logistics combining passenger and freight flows through mathematical programming. *J. Intell. Transp. Syst.* **11**, 1–16 (2023).
14. Bruzzone, F., Nocera, S. & Pesenti, R. Feasibility and optimization of freight-on-transit schemes for the sustainable operation of passengers and logistics. *Res. Transp. Econ.* **101**, 101336 (2023).
15. Hu, W., Dong, J., Hwang, B.-G., Ren, R. & Chen, Z. Is mass rapid transit applicable for deep integration of freight-passenger transport? A multi-perspective analysis from urban China. *Transp. Res. Part Policy Pract.* **165**, 490–510 (2022).
16. Lin, J., Zhou, W. & Du, L. Is on-demand same day package delivery service green?. *Transp. Res. Part Transp. Environ.* **61**, 118–139 (2018).
17. Labarthe, O., Ahmadi, G., Klibi, W., Deschamps, J.-C. & Montreuil, B. A sustainable on-demand urban delivery service enabled by synchromodality and synergy in passenger and freight mobility. *Transp. Res. Part C Emerg. Technol.* **161**, 104544 (2024).
18. Li, F., Guo, X., Zhou, L., Wu, J. & Li, T. A capacity matching model in a collaborative urban public transport system: integrating passenger and freight transportation. *Int. J. Prod. Res.* **60**, 6303–6328 (2022).
19. Mohri, S. S., Nassir, N., Lavieri, P. S. & Thompson, R. G. Modeling package delivery acceptance in Crowdshipping systems by public transportation passengers: A latent class approach. *Travel Behav. Soc.* **35**, 100716 (2024).
20. Masson, R. et al. Optimization of a city logistics transportation system with mixed passengers and goods. *EURO J. Transp. Logist.* **6**, 81–109 (2017).
21. Kawa, A. Out-of-home delivery as a solution of the last mile problem in e-commerce. In *Smart and Sustainable Supply Chain and Logistics – Trends, Challenges, Methods and Best Practices: Volume 1* (eds Golinska-Dawson, P. et al.) 25–40 (Springer International Publishing, 2020). https://doi.org/10.1007/978-3-030-61947-3_2.
22. Wollenburg, J., Hübner, A., Kuhn, H. & Trautrims, A. From bricks-and-mortar to bricks-and-clicks: Logistics networks in omni-channel grocery retailing. *Int. J. Phys. Distrib. Logist. Manag.* **48**, 415–438 (2018).
23. Salimifard, K. & Bigharaz, S. The multicommodity network flow problem: state of the art classification, applications, and solution methods. *Oper. Res.* **22**, 1–47 (2022).

24. Kafle, N., Zou, B. & Lin, J. Design and modeling of a crowdsource-enabled system for urban parcel relay and delivery. *Transp. Res. Part B Methodol.* **99**, 62–82 (2017).
25. Hagen, T. & Scheel-Kopeinig, S. Would customers be willing to use an alternative (chargeable) delivery concept for the last mile?. *Res. Transp. Bus. Manag.* **39**, 100626 (2021).
26. Mousavi, K., Bodur, M. & Roorda, M. J. Stochastic last-mile delivery with crowd-shipping and mobile depots. *Transp. Sci.* **56**, 7584 (2022).
27. Cheng, G., Guo, D., Shi, J. & Qin, Y. Smart city-wide package distribution using crowdsourced public transportation systems. *IEEE Int. Things J.* **6**, 7584–7594 (2019).
28. Wu, W., Ma, W., Long, K., Zhou, H. & Zhang, Y. Designing sustainable public transportation: integrated optimization of bus speed and holding time in a connected vehicle environment. *Sustainability* **8**, 1170 (2016).
29. Agrawal, A., Kumar, M., Prajapati, D., Singh, M. & Kumar, P. Smart public transit system using an energy storage system and its coordination with a distribution grid. *Intell. Transp. Syst. IEEE Trans. On* **15**, 1622–1632 (2014).
30. Wang, Z. & Tang, Y. Research on Availability of Intelligent Express Cabinet Service System. In: *Advances in Usability, User Experience, Wearable and Assistive Technology* (eds. Ahram, T. & Falcão, C.) (Springer International Publishing 2020). Pp 356–363. https://doi.org/10.1007/978-3-030-51828-8_46.
31. Le, T. V., Stathopoulos, A., Van Woensel, T. & Ukkusuri, S. V. Supply, demand, operations, and management of crowd-shipping services: A review and empirical evidence. *Transp. Res. Part C Emerg. Technol.* **103**, 83–103 (2019).
32. Shen, H. & Lin, J. Investigation of crowdshipping delivery trip production with real-world data. *Transp. Res. Part E Logist. Transp. Rev.* **143**, 102106 (2020).
33. Pongprasert, P. & Kubota, H. TOD residents' attitudes toward walking to transit station: a case study of transit-oriented developments (TODs) in Bangkok. *Thailand J. Mod. Transp.* **27**, 39–51 (2019).
34. Cheng, R., Jiang, Y. & Nielsen, O. A. Investigating using urban public transport for freight deliveries. *Transp. Rev.* **43**, 997–1020 (2023).
35. Chen, C., Pan, S., Wang, Z. & Zhong, R. Y. Using taxis to collect citywide E-commerce reverse flows: a crowdsourcing solution. *Int. J. Prod. Res.* **55**, 1833–1844 (2017).
36. Liu, L. & Miller, H. J. Measuring the impacts of dockless micro-mobility services on public transit accessibility. *Comput. Environ. Urban Syst.* **98**, 101885 (2022).
37. Gläser, S., Jahnke, H. & Strassheim, N. Opportunities and challenges of crowd logistics on the last mile for courier, express and parcel service providers–a literature review. *Int. J. Logist. Res. Appl.* **11**, 1–29 (2021).

Acknowledgements

Author contributions

Gao Gao: Data curation, Investigation, Writing- Original draft preparation,Software. Zhengfeng Huang: Conceptualization, Methodology, Validation, Reviewing and editing. Pengjun Zheng:Validation.

Declarations

Competing interests

The authors declare no competing interests.

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