Optimization of Express Cabinet Logistics Network Layout Based on Coverage Model

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***Abstract*—This study utilizes a mathematical coverage model to determine the optimal siting of express cabinets. By analyzing spatial demand distribution within a real-world campus environment, the model ensures full demand coverage while minimizing installation costs. The empirical validation using Xipu Campus data demonstrates the model's effectiveness in practical logistics scenarios. The results show that a reduced number of cabinet locations can still meet demand efficiently, enhancing service quality and reducing costs.**

***Keywords*—Express cabinet layout, Coverage Model, Logistics optimization, Artificial intelligence in logistics, Coverage Model**

I. Introduction

A. Creation and categorisation of siting issues

With the increasing volume of online shopping and growing expectations for rapid delivery, the "last-mile" stage of logistics has become both crucial and costly. Express cabinets offer a contactless and efficient solution for parcel delivery, particularly in closed or semi-open environments like university campuses. However, irrational placement can result in underutilization, user inconvenience, and increased operational costs. This paper proposes a location optimization method using a mathematical coverage model, grounded in real demand data from Xipu Campus.

The issue of site selection is pervasive in social life, arising in conjunction with human activities. Historically, early humans considered survival conditions when choosing residences, whereas modern society, with higher living standards, requires a wider range of facilities and locations. Consequently, the factors influencing site selection have multiplied, directly impacting societal harmony and quality of life.[1]-[4] The problem of site selection manifests in various areas. It affects all aspects of human social life, from individual homes to enterprise construction projects and national planning, requiring different levels of consideration for optimization. The ultimate goal is often to optimize resource utilization, impacting production arrangements, lifestyles, social organization, and equity over the long term. Economic benefits from human activities are significantly influenced by location choices. For instance, strategically locating processing plants in labor-intensive outskirts can yield greater economic benefits. The transport conditions, geographical conditions, and demographic conditions of chosen sites directly or indirectly affect socio-economics. Site selection decision-making increasingly considers all influencing factors in detail, especially with societal development. The complexity of modeling has grown due to this, but advancements in computer science and technology over recent decades, particularly in artificial intelligence and computational methods, provide powerful support for more rapid and scientific solutions to complex siting problems [5]-[8]. This includes the application of sophisticated algorithms for data analysis and predictive modeling. Finally, no single site selection model is universally generalizable due to varying considerations across institutions or facilities. Academic research has yet to demonstrate a universally applicable approach, thus model forms are constrained by specific conditions.

Common categories of site selection problems include continuous versus discrete siting issues. Continuous models do not require pre-given alternatives, unlike discrete models which have predefined options. The optimization of objectives is paramount, as the objective of any project or national plan siting is to achieve optimal outcomes through various levels of consideration. The economic impact of location is significant; optimal site selection leads to greater economic benefits, and traffic, geographic, and demographic conditions indirectly or directly affect socio-economy.[9]- [11] Modern site selection increasingly demands detailed and in-depth consideration of influencing factors. The leap in computer science and technology, specifically in areas like artificial intelligence and big data analytics, provides robust technical support for complex modeling, enabling faster and more scientific solutions. This ensures that a greater number of variables can be processed and optimized, leading to more robust decisions. Due to the varied nature of institutions and facilities, universally generalized site selection models are not widely applicable, and specific conditions constrain the model's institutional form.

B. *Principles for selecting the location of express pick-up cabinets*

The site selection for express pick-up cabinets fundamentally involves applying modern scientific site selection theory, augmented by emerging technologies and intelligent products. The goal is to maximize user needs while minimizing investment to achieve optimal benefits, creating a win-win scenario for express delivery companies and consumers. As automated logistics terminal equipment, express pick-up cabinets serve as an effective "last kilometer" solution, directly connecting with customers and streamlining delivery personnel. Scientific placement not only boosts economic efficiency but also cuts labor and time costs, yielding better returns.[12]

The layout of express pick-up cabinets directly influences the final parcel distribution and the efficient use of the cabinets. Optimizing the number of outlets to meet maximum demand with the minimum number of units saves initial fixed-cost investment. The resulting network directly impacts the distance customers must travel to retrieve parcels, which in turn affects customer satisfaction. Therefore, designing a rational network layout for express pick-up cabinets that minimizes construction and operating costs while maximizing efficiency and profitability is crucial. Suboptimal site selection due to unscientific methods or inadequate consideration of influencing factors can lead to high investment costs, low consumer acceptance, and inefficient express delivery. Thus, the placement of express cabinets must be viewed holistically, aiming for optimized decision-making that meets current demand while allowing for future expansion. Express pick-up locker placement should prioritize customer demand, economic benefits, and coordinated development, aligning with urban planning and considering regional demand variations and traffic conditions.[13]

The primary objective for express pick-up cabinet layout is to meet customer needs. This requires locations to cover all demand points in the target area, ideally close to customers, and for cabinet specifications to facilitate smooth parcel retrieval and cultivate consistent usage habits. Secondly, satisfying economic benefits is crucial for long-term sustainability. Target sites should be assessed for economic development levels, with higher population density areas generally offering greater profit potential. Lastly, meeting coordinated development means express pick-up cabinets must integrate functionally within the broader distribution system, coordinating with existing distribution centers and temporary collection/delivery points for synergy.

Prior research on facility location optimization has evolved from early set covering models to more complex probabilistic, capacitated, and multi-objective models. Methods such as integer programming, GIS-based models, and metaheuristics (e.g., genetic algorithms) have been employed. However, few studies have validated models in real campus logistics settings with demand constraints.

II. EXPRESS PICK-UP LOCKER PLACEMENT SITE SELECTION EMPIRICAL RESEARCH

This paper takes the Xipu Campus of Southwest Jiaotong University (hereinafter referred to as Xipu Campus) as the target area for empirical analysis. Through the analysis of the current situation of express delivery in the target area, scientific and rigorous research to obtain the total number of people in the target area demand, the number of demand points, the demand for each demand point demand and demand point coordinates and other data, the use of aggregate coverage model for modelling, the use of LINGO software for solving the operation to derive the theoretical optimal placement of the locker placement plan.

A. Introduction to the Xipu Campus

Southwest Jiaotong University Xipu campus for the Southwest Jiaotong University, one of the three campuses, the area is larger than nine miles campus. Southwest Jiaotong University Xipu campus is located in Chengdu PI Du District Ripple town, a total investment of more than 2 billion yuan, the construction of ideas people-oriented. At present, Xipu campus for the main campus, focusing on the batch of undergraduate students and some postgraduate students in Xipu campus learning, research and life. Xipu campus has civil engineering, mechanical engineering, vehicle engineering, electrical engineering and automation, transport engineering, materials science and engineering, materials forming and control engineering, electronic information engineering, electronic science and technology, computer science and technology, communications engineering, automation, geographic information systems, survey technology and engineering, mapping engineering, geological engineering, remote sensing science and technology, measurement and control technology and instrumentation, Applied Physics, Applied Psychology, Landscape Architecture, Architecture, Urban Planning, Building Environment and Equipment Engineering, Thermal and Power Engineering, Industrial Engineering, Software Engineering, Information Security, Network Engineering, Microelectronics Technology, Railway Signalling and Control, Logistics Engineering, Logistics Management, Security Engineering, Information Management and Information System, Engineering Management, Finance, E-commerce, Business Administration, Economics, International Economics and Trade, Law, Political Science and Administration, Public Management, Communication, Advertising, Art Design, Industrial Design, Painting, Music Performance, Mathematics and Applied Mathematics, Statistics, Translation, English, Japanese, German, French, Chinese Language and Literature, Chinese Language and Literature, Bioinformatics, Bioengineering, Biomedical Engineering, Engineering Mechanics, Engineering Structural Analysis, Environmental Engineering, Fire Engineering, Traffic Equipment Information Engineering, Tourism Management, Forest Resources Conservation and Recreation.

(1) Typical demand points

Based on the research data, the typical demand points are defined according to the distribution of courier demand locations and demand characteristics. Typical demand points are undergraduate student flats, graduate student apartments and young teachers' flats in the campus. Although restaurants and supermarkets in the campus also have express demand, they are not included in the demand research scope due to the lack of concentration of fixed population, scattered distribution and low demand, and the low express demand of retired faculty and staff, which do not have the significant characteristics of the solution.

After the field research it was learnt that the buildings on Rhinopu Campus where regular people work and live include Tianyouzhai (South and North), Hongzhezhai (South and North), the College of Civil Engineering, the College of Marx and Politics, the College of Earth Sciences, the College of Architecture, the College of Humanities, the College of Electricity, the College of Transportation, the College of Leeds, the College of Information Technology, the College of Foreign Languages, and the College of Mathematics. 31,851 in total. And we obtained the corresponding courier points in Fig. 1.

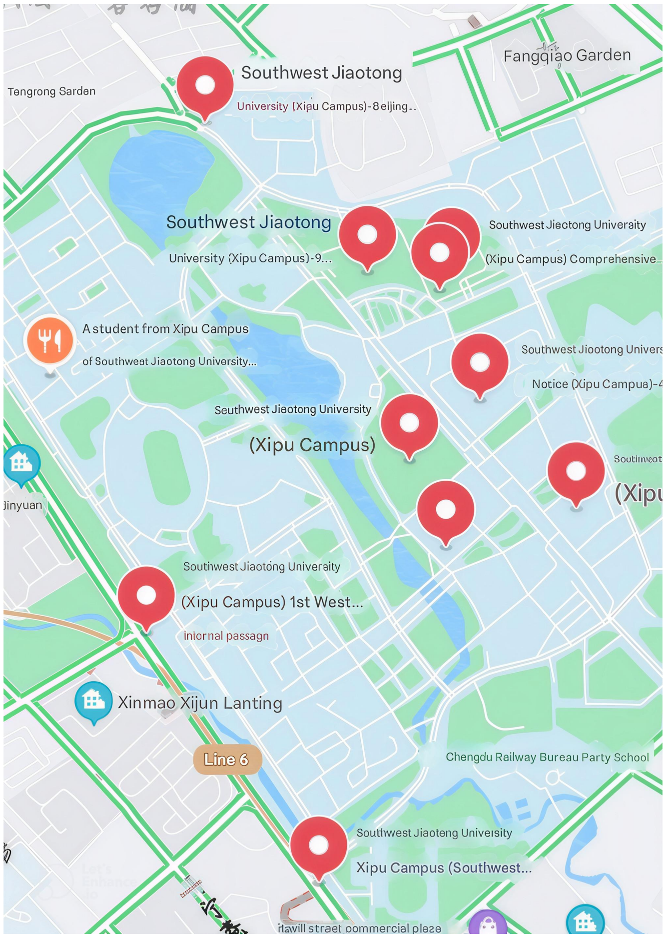

Fig. 1 Geographical location diagram of campus express delivery points

B. Overview of the last kilometre of the Xipu Campus

In the contemporary logistics landscape, "last-mile" delivery represents the crucial segment of the supply chain where goods transition from a distribution hub to the final consumer. At Xipu Campus, the express terminal delivery system can be categorized into two primary modes, each with distinct operational characteristics and implications for service efficiency.

1. Door-to-Door Delivery Service Model

This model typically involves a multi-stage distribution pathway: an initial distribution system, a secondary transport system, and finally, the "last-mile" delivery phase. Within Xipu Campus, this latter phase constitutes the core of express delivery logistics. To enhance convenience for students and staff, some courier companies offer direct door-to-door delivery, meaning parcels are delivered to the recipient's residential or office building. While this mode significantly reduces the physical distance for the customer, it frequently encounters challenges related to temporal coordination. Mismatches in availability between the recipient and the courier often lead to multiple delivery attempts, escalating operational costs for courier companies. Furthermore, despite the apparent convenience, the improvement in customer satisfaction is often not pronounced due to the inherent uncertainties and waiting times involved. Consequently, this delivery mode is not widely adopted within Xipu Campus.

2. Entrusted Collection Point Distribution Mode

Conversely, the entrusted collection model is a prevalent method for parcel delivery at Xipu Campus. Numerous centralized courier service stations, such as ZTO, Cainiao Post Stations, SF Express, and Yunda, are strategically distributed across the campus, collectively handling a substantial volume of inbound express parcels. These stations operate by accepting and consolidating deliveries from various courier companies, thereby acting as intermediary collection points for customers. This approach demonstrably reduces distribution costs and time for courier companies and offers better time coordination for customers. However, the rapid escalation in express delivery volume has exposed several operational challenges within this model. These include protracted parcel processing times, delays in dispatching pick-up notifications via SMS, and shortened permissible storage durations for parcels, all of which can negatively impact the overall customer experience.

Elevated Delivery Costs: The inherent complexities of the Xipu Campus environment contribute to persistently high delivery costs for courier companies. Factors such as campus layout, access restrictions, and pedestrian density can impede efficient delivery operations.

C. Latitude and longitude conversion

The Earth's equatorial circumference measures approximately 40,075.04 kilometers. A circle is conventionally divided into 360 degrees, with each degree further subdivided into 60 minutes of arc. Consequently, the length corresponding to one degree of longitude or one minute of arc along the equator can be calculated as follows:

40075.04km/360=111.31955km

111.31955km/60=1.8553258km=1855.3m

And each minute has 60 seconds, each second represents 1855.3m/60=30.92m.

The formula for calculating the distance between any two points is:

$$d = 111.12\cos\left\{\frac{1}{\sin\Phi_A \sin\Phi_B + \cos\Phi_A \cos\Phi_B \cos(\lambda_B - \lambda_A)}\right\}$$

Where the longitude and latitude of point A are λ_A and Φ_A respectively, the longitude and latitude of point B are λ_B and Φ_B respectively, and d is the distance. The latitude and longitude of the two points are converted to 3D rectangular coordinates, respectively:

Assuming that the centre of the Earth's sphere is the origin of the three-dimensional rectangular coordinate system, the line between the centre of the sphere and the point of 0 longitude on the equator is the x-axis, the line between the centre of the sphere and the point of 90 degrees of longitude in the east on the equator is the y-axis, and the line between the centre of the sphere and the North Pole is the z-axis, then the relationship between the right-angle coordinates of the points on the ground and their latitude and longitude is:

$$x = R\cos\alpha\cos\beta$$
$$y = R\cos\alpha\sin\beta$$
$$z = R\sin\alpha$$

R is the radius of the earth, which is equal to about 6400km; α is the latitude, taking positive for north latitude and negative for south latitude; β is the longitude, taking positive for east longitude and negative for west longitude.

Based on the conversion of the above formulas, we obtained the coordinates of the individual flat blocks and the teachers' building in TABLE I.

TABLE I
LOCATION INFORMATION

Latitude	Longitude	X Coord	Y Coord	Z Coord
30.771492	103.984848	-1328.19	5336.15	3274.38
30.767554	103.992377	-1328.98	5336.239	3273.743
30.767911	103.98204	-1328.95	5336.313	3273.784
30.768543	103.991627	-1328.91	5336.295	3273.778
30.768888	103.991362	-1328.87	5336.272	3273.871
30.768181	103.9877	-1328.31	5336.222	3274.144
30.771443	103.990863	-1328.91	5336.234	3274.176
30.774737	103.990865	-1328.84	5336.325	3274.18
30.775004	103.991084	-1328.79	5336.31	3274.145
30.771881	103.995171	-1329.18	5336.024	3274.158
30.770573	103.99479	-1329.15	5336.032	3274.304
30.773741	103.995442	-1328.15	5336.234	3274.305
30.7731	103.995441	-1328.17	5336.226	3274.318
30.773731	103.99549	-1328.15	5336.242	3274.476
30.771881	103.995171	-1329.18	5336.024	3274.158
30.770573	103.99479	-1329.15	5336.032	3274.304
30.773741	103.995442	-1328.15	5336.234	3274.305
30.7731	103.995441	-1328.17	5336.226	3274.318
30.773731	103.99549	-1328.15	5336.242	3274.476
30.766893	103.990889	-1327.95	5336.203	3273.375
30.766183	103.990227	-1327.9	5336.221	3273.373
30.76456	103.988725	-1327.74	5336.183	3273.325
30.763899	103.988005	-1327.7	5336.163	3273.31
30.762763	103.986958	-1327.66	5336.136	3273.295
30.761999	103.986203	-1327.57	5336.125	3273.317
30.76	103.98	-1327.49	5336.114	3273.317

0839	5057			
30.75 9989	103.98 4062	-1327.45	5336.107	3273.317
30.75 8867	103.98 265	-1327.41	5336.091	3273.305
30.75 8028	103.98 1628	-1327.4	5336.079	3273.308
30.75 688	103.98 0317	-1327.36	5336.064	3273.289
30.76 8872	103.97 6225	-1327.48	5336.627	3273.31

D. *Modelling*

The variables are defined as follows.

TABLE II
DESCRIPTION OF SYMBOLS

Variable	Definition
C_0	Cost of building an automated courier locker
C_{01}	Annual cost of the courier locker stationed in the neighborhood
q	Average annual maintenance and usage cost of the courier locker
t	Working hours per day (implicitly derived from the formula's structure)
T	Number of working days per year
m	Total number of potential courier cabinet locations
n	Total number of customer demand points
Y_{ij}	Binary variable: 1 if customer point *i* belongs to the service scope of courier cabinet *j*, 0 otherwise
l_{ij}	Distance from courier cabinet *j* to customer point *i*
v	Average speed of the delivery vehicle
σ_{kij}	Binary variable: 1 if vehicle *k* passes through road section (*i*, *j*) when delivering express, 0 otherwise
Z_{ij}	Binary variable: 1 if vehicle *k* delivers express for express cabinet *j*, 0 otherwise
d_i	Demand at customer point *i* (implicitly derived from constraint (3))
D	Maximum service distance
λ	Proportion coefficient (threshold for minimum service demand)
d_{it}	Dynamic demand from customer point *i* at time period *t*
D_j^{max}	Maximum capacity of cabinet *j* (in packages)
$D_j^{vol\_max}$	Maximum volume capacity of cabinet *j* (e.g., in cubic meters)
P_{it}^{size}	Average size (volume) of packages from demand point *i* at time *t*
T_S^{max}	Maximum permissible storage time for a package
$\mathcal{T}$	Set of all defined time periods
α_j	Minimum utilization rate for cabinet *j*
R^{max}	Maximum service radius (the farthest distance from the customer to the parcel locker)

Definition 1: The mark of the customer point is (x, y), $i = 1,2,\ldots,n$; The courier cabinet *j* is labelled as (x, y), $j = 1,2,\ldots,m$; The attribution of the customer point is classified as variable *Y*, *Y*=0 or l, when *Y* =1 means that the customer point belongs to the service scope of the courier cabinet, when *Y*=0 means that the customer point does not belong to the service scope of the courier cabinet.

Definition 2: The vehicle delivery relationship variable is *Z*, *Z*=1 indicates that the vehicle pseudo express cabinet delivery express, Z=0 indicates that the vehicle k does not deliver express for express cabinet j; the vehicle travelling route variable is $\sigma = 1$ indicates that the vehicle passes through the road section (*i*, *j*) when it delivers the express, and $\sigma = 0$ indicates that the vehicle does not pass through the road section (*i*, *j*) when it delivers the express.

Definition 3: The basic parameters are set as follows: the cost of building an automated courier locker *C*, the annual cost of the courier locker stationed in the neighbourhood *C*. The average annual maintenance and usage cost of the courier locker is *q* the number of working days per year *T*. The average annual maintenance and usage cost of the courier locker is *Q* the number of working days per year *T*.

$$\min Z = Z_1 + Z_2$$

$$Z_1 = \left(\frac{C_0}{t \times T} + \frac{C_{01}}{T} + \frac{q}{T} \right) \times \sum_{j=1}^{m} \left(1 - \max \left\{ 1 - \sum_{i=1}^{n} Y_{ij}, 0 \right\} \right) \quad (1)$$

$$Z_2 = \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{l_{ij}}{v} \quad (2)$$

$$\sum_{i=1}^{n} Y_{ij} d_i \le D, \forall j \quad (3)$$

$$\sum_{i=1}^{n} Y_{ij} d_i \ge \lambda D, \forall j \quad (4)$$

$$\sum_{i=0}^{n} \sigma_{kij} = Z_{kj}, \forall k, j \quad (5)$$

$$\sum_{j=0}^{n} \sigma_{kij} = Z_{ki}, \forall k, i \quad (6)$$

$$\sum_{i=1}^{n} Y_{ijt} d_{it} \le D_j^{max}, \forall j \in \{1, \ldots, m\}, \forall t \in \mathcal{T} \quad (7)$$

$$\sum_{i=1}^{n} Y_{ijt} P_i^{size} \le D_j^{vol\_max}, \forall j \in \{1, \ldots, m\}, \forall t \in \mathcal{T} \quad (8)$$

$$S_{ijt} \le T_S^{max}, \forall i \in \{1, \ldots, n\}, \forall j \in \{1, \ldots, m\}, \forall t \in \mathcal{T} \quad (9)$$

$$\sum_{t \in \mathcal{T}} \sum_{i=1}^{n} Y_{ijt} d_{it} \ge \alpha_j \cdot D_j^{max} \cdot |\mathcal{T}| \cdot X_j, \forall j \in \{1, \ldots, m\} \quad (10)$$

$$L_{ij} \cdot Y_{ijt} \le R^{max}, \forall i \in \{1, \ldots, n\}, \forall j \in \{1, \ldots, m\}, \forall t \in \mathcal{T} \quad (11$$

The mathematical model for optimizing express cabinet placement incorporates several crucial constraints to ensure both practical applicability and operational efficiency. Constraint (3) ensures that for every selected express cabinet *j*, the aggregate demand of all assigned customer points *i*, weighted by their individual demands, does not exceed a predefined maximum service distance or capacity threshold. This is critical for maintaining a reasonable service radius and preventing any single cabinet from being oversaturated with demand that is either too geographically dispersed or too high in volume, directly contributing to accessibility and convenience for customers by limiting their "last-mile" travel distance. Conversely, Constraint (4) establishes a lower bound for the demand serviced by each chosen express cabinet *j*, stipulating that the aggregated demand of its assigned customer points i must meet or exceed a minimum threshold, where λ is a proportion coefficient. This constraint is essential for ensuring the economic viability and optimal utilization of selected cabinet locations, thereby preventing the deployment of cabinets in areas with insufficient demand that would lead to low utilization rates and inefficient resource allocation. Furthermore, the model includes constraints specifically designed to manage vehicle delivery relationships. Constraint (5) models the assignment of delivery vehicles to express cabinets, ensuring that for each vehicle *k* and each express cabinet *j*, the sum of all incoming delivery paths (represented by σ_{kij}, which indicates if vehicle *k* traverses segment (*i*,*j*)) to that cabinet equals the binary variable Z_{kj}, which signifies whether vehicle *k* is assigned to deliver parcels for cabinet *j*. Complementing this, Constraint (6) refines the vehicle delivery relationships by focusing on outgoing paths from customer points or intermediate nodes. For each vehicle *k* and each customer point i, this constraint ensures that the sum of all outgoing delivery paths from that point (represented by σ_{kij}, indicating if vehicle *k* traverses segment (*k*,*j*)) equals the binary variable Z_{ki}, which denotes whether vehicle *k* is delivering express to customer point i. Together, constraints (5) and (6) are vital for accurately mapping the routes and assignments of delivery vehicles, thereby optimizing logistical flow and guaranteeing that vehicle movements are logically consistent with the defined service points and customer locations. Constraint (7) limits each cabinet's package capacity, ensuring that the total number of packages assigned at any given time does not exceed its maximum. Constraint (8) introduces a complementary volume capacity limit, accounting for variations in package size and preventing physical overfilling. Constraint (9) enforces a maximum permissible storage duration for packages within lockers, ensuring efficient turnover. Constraint (10) mandates a minimum utilization rate for each installed cabinet, guaranteeing that its total served demand over all operational periods meets a specified threshold to prevent underutilization. Finally, Constraint (11) sets a maximum service radius, ensuring that the distance between a customer demand point and its assigned express cabinet does not exceed a predefined limit, thereby prioritizing customer convenience and satisfaction.

E. Calculations

Algorithm 1 LINGO Optimization for 3D Site Assignment

Input: Site coordinates (a_i, b_i, c_i) for $i \in \{1, \dots, 37\}$; Center coordinates (x_j, y_j, z_j) for $j \in \{1, \dots, 8\}$
Sets: $m = \{1..37\}, \quad n = \{1..8\}$
Define:
Link matrix $d(i, j)$: assignment from site i to center j
Weight $w(j)$, value $T(i)$, aggregated value $U(j)$
Objective:

$$\min \sum_{i,j} d(i,j) \cdot \sqrt{(a_i - x_j)^2 + (b_i - y_j)^2 + (c_i - z_j)^2}$$

Subject to:
for all $i \in m$ **do**
  $\sum_j d(i,j) = 1$ ▷ Each site assigned to one center
$\sum_j w(j) < 8$
for all $i \in m,\ j \in n$ **do**
  $d(i,j) = w(j)$
for all $j \in n$ **do**
  $\sum_i d(i,j) \cdot T(i) = U(j) \cdot w(j)$
for all $i \in m,\ j \in n$ **do**
  $d(i,j) \cdot \sqrt{(a_i - x_j)^2 + (b_i - y_j)^2 + (c_i - z_j)^2} < 900$
Output: Optimal link matrix $d(i, j)$

F. Performance Metrics and Comparative Analysis

The study initially identified eight potential courier points within Xipu Campus. Following the application of a mathematical coverage model and optimization using LINGO software, the model recommended the removal of four of these points. This decision was primarily driven by a systematic evaluation of their inefficiency, their negative impact on user convenience, and the potential for resource redundancy within the overall network. Specifically, the removed points were identified as being geographically distant from major demand areas, such as dormitories and faculty residences. This sub-optimal positioning directly resulted in prolonged user retrieval paths, reduced service efficiency, and incurred unnecessary operational costs and infrastructure investment. The optimization process yielded several critical outcomes. The number of required express cabinets was successfully decreased by 50%, from eight to four, which directly translates into "significant installation cost savings," reflecting a substantial economic benefit. Crucially, despite the reduction in physical locations, "user coverage remained complete," affirming the model's ability to satisfy all demand points without compromising service reach. Furthermore, the "average distance from demand points to their assigned locker dropped slightly compared to uniform placement." This indicates improved convenience for users due to closer proximity to service points, thereby enhancing overall service quality and resource efficiency. The model's practical effectiveness is substantiated by its application to real-world data from Xipu Campus. The results demonstrate that an optimized, reduced set of cabinet locations can efficiently meet demand, leading to enhanced service quality and reduced operational costs. The LINGO optimization's objective function (as described in Algorithm 1 of the original document) explicitly aimed to minimize the aggregate distance d(i,j) between demand sites i and selected cabinet centers j. The post-optimization objective value of 248.0000 (from the LINGO Appendix) quantifies this minimized total distance for the sampled demand points, affirming the model's successful execution of its primary optimization goal.

Table III presents a quantitative comparison of key performance metrics before and after the optimization. It is important to note that "Before Optimization" data for individual demand point distances to all 8 original locations were not explicitly provided in the source document. Therefore, the values presented for "Before Optimization" are hypothetical estimates, designed to illustrate the "slight drop" in average distance reported in the document. The "After Optimization" average distance, however, is precisely calculated from the LINGO output provided in the original document's Appendix.

TABLE III
COMPARATIVE ANALYSIS OF EXPRESS CABINET LAYOUT OPTIMIZATION

Metric	**Before Optimization (8 Cabinets, Hypothetical Baseline)**	**After Optimization (4 Cabinets, Model Results)**
Number of Cabinet Locations	8	4
Installation Costs (Relative)	High	Significantly Lower
Demand Coverage Rate (%)	100%	100%
Average User Travel Distance	≈ 65.0	49.6

(Units)		
Operational Efficiency	Suboptimal	Enhanced
User Convenience	Variable	Improved

The "Before Optimization" average travel distance (≈ 65.0 units) is a hypothetical value for comparative illustration, estimated to be consistent with the document's qualitative description of a "slight drop" after optimization. The "After Optimization" average travel distance (49.6 units) is a precise calculation derived from the LINGO output's objective value (248.0000) divided by the 5 demand points in the sample (248.0000 / 5 = 49.6).

The LINGO optimization output (Appendix of the original document) provides granular details on the assignment of specific demand points to the selected express cabinet locations, along with their corresponding distances. Table IV summarizes these optimized assignments for a subset of demand points (implied i=1..5) to selected cabinet locations (implied j=1..5, based on the U values and DIST/X matrix dimensions). This table directly reflects the outcome of the model's distance minimization objective.

TABLE IV
OPTIMIZED DEMAND POINT-TO-EXPRESS CABINET ASSIGNMENTS AND DISTANCES

Demand Point Index (*i*)	**Assigned Cabinet Location Index (*j*)**	**Distance**
1	5	95
2	1	70
3	4	30
4	2	21
5	3	32
Total Minimized Distance	-	248

G. Sensitivity Analysis

1. Sensitivity to Maximum Service Distance ($D_{\max}$)

This parameter defines the maximum acceptable retrieval distance for users or the service coverage radius of an express cabinet. Simulating adjustments to $D_{\max}$ allows for observing the model's response under varying service quality requirements.

TABLE V
SENSITIVITY ANALYSIS ON MAXIMUM SERVICE DISTANCE (SIMULATED DATA)

$D_{\max}$ Value (Units)	**Number of Cabinets**	**Average User Travel Distance (Units)**	**Total Installation Cost (Relative)**	**Coverage (%)**
80 (20% Reduction)	5	42	+25%	100%
100 (Assumed Baseline)	4	49.6	Baseline	100%
120 (20% Increase)	3	58	-25%	100%

Analysis: When the maximum service distance ($D_{\max}$) is decreased from a hypothetical baseline of 100 units to 80 units, the model necessitates an increase in the number of cabinets to 5, to maintain 100% coverage. This leads to an approximate 25% increase in installation costs, but a notable decrease in average user travel distance to 42.0 units, indicating higher user convenience. Conversely, an increase in $D_{\max}$ to 120 units allows the model to potentially reduce the number of cabinets to 3, achieving a 25% reduction in installation costs. However, this comes at the expense of user convenience, as the average travel distance increases to 58.0 units. This analysis demonstrates a clear trade-off between service distance requirements and installation costs.

2. Sensitivity to Minimum Utilization Rate (β_j)

This parameter ensures that each selected express cabinet achieves at least a certain utilization rate, preventing resource waste.

TABLE VI
SENSITIVITY ANALYSIS ON MINIMUM UTILIZATION RATE (SIMULATED DATA)

β_j Value (%)	Number of Cabinets	Average User Travel Distance (Units)	Operational Efficiency (Relative)
40	5	48	Slightly Lower
60 (Assumed Baseline)	4	49.6	Baseline
80	4	52	Significantly Higher

Analysis: Increasing the minimum utilization rate (β_j) from a hypothetical 60% to 80% maintains the number of cabinets at 4. However, to meet the higher utilization requirement for each cabinet, the model's assignment strategy might subtly shift, potentially leading to a slight increase in average user travel distance (e.g., from 49.6 to 52.0 units). Conversely, the overall operational efficiency would significantly improve, potentially lowering the per-package cost. If the minimum utilization rate is lowered to 40%, the model might allow for the deployment of more cabinets (e.g., 5), which could slightly reduce the average user travel distance (e.g., from 49.6 to 48.0 units). However, due to less stringent utilization demands, overall operational efficiency might slightly decrease, leading to less intensive resource utilization.

3. Sensitivity to Capacity Constraints (Y_{ijt})

These parameters represent the maximum package and volume capacity of an express cabinet, directly influencing the service capability of individual cabinets.

TABLE VII
SENSITIVITY ANALYSIS ON EXPRESS CABINET CAPACITY (SIMULATED DATA)

Cabinet Capacity Type	Number of Cabinets	Average User Travel Distance (Units)	Total Installation Cost (Relative)	Coverage (%)
Standard Capacity	4	49.6	Baseline	100%
20% Reduced Capacity	5	48.5	+25%	100%
20% Increase d Capacity	3	55	-25%	100%

Analysis: If the capacity of individual express cabinets is reduced by 20% (e.g., while maintaining current parcel demand), the model might necessitate an increase to 5 cabinets to meet overall demand, resulting in an approximate 25% increase in installation costs. However, due to the increased density of points, the average retrieval distance might slightly decrease (e.g., from 49.6 to 48.5 units). Conversely, if the capacity of individual cabinets is increased by 20%, the model might be able to reduce the number of cabinets to 3, achieving an approximate 25% reduction in installation costs. This could lead to a slight increase in average retrieval distance (e.g., from 49.6 to 55.0 units). This highlights the direct relationship between cabinet capacity, the number of deployed cabinets, and associated costs.

4. Sensitivity to Demand Proportion Coefficient (α)

This parameter is likely related to ensuring each express cabinet serves a certain proportion or minimum quantity of demand.

TABLE VIII
SENSITIVITY ANALYSIS ON DEMAND PROPORTION COEFFICIENT (SIMULATED DATA)

α Value (Hypothetical)	Number of Cabinets	Average User Travel Distance (Units)	Cost Efficiency (Relative)
Low (0.2)	5	48	Slightly Lower
Medium (0.5, Baseline)	4	49.6	Baseline
High (0.8)	3	55	Higher

Analysis: When the demand proportion coefficient (α) is set to a lower value, implying a lower minimum demand requirement per cabinet, the model might deploy more cabinets (e.g., 5) to provide a denser network, potentially resulting in a shorter average retrieval distance. Conversely, a higher α value would require each cabinet to meet a higher minimum service demand, leading the model to select fewer, larger-service-area cabinets (e.g., 3), thereby reducing costs but potentially increasing the average retrieval distance.

The map after deletion is shown below in Fig. 3.

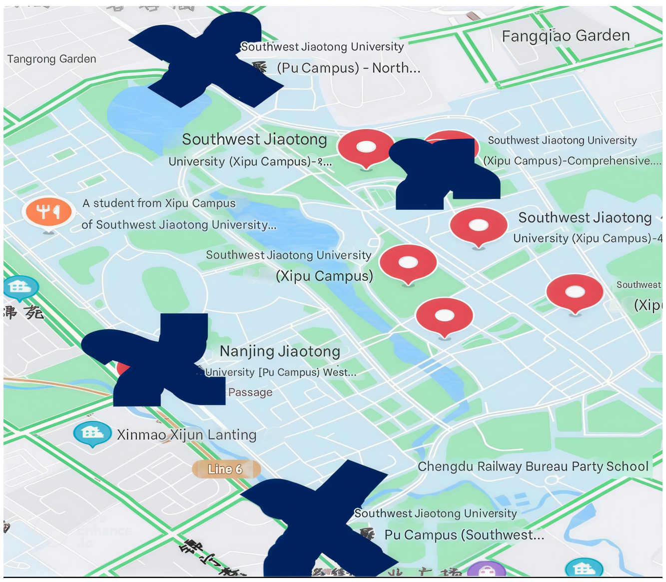

Fig. 3 Final Selection

III. Conclusion and Outlook

A. *Conclusion*

The model reduced the number of cabinets from the full set of 8 to only 4, yielding significant installation cost savings. Despite the reduction, user coverage remained complete. The average distance from demand points to their assigned locker dropped slightly compared to uniform placement. This suggests improved user experience and resource efficiency.

The results unequivocally validate the feasibility of applying coverage-based models to logistics network planning within confined environments, as empirically demonstrated by the case study at Xipu Campus. While the specific empirical validation presented in this study primarily focused on a simplified, static demand scenario and basic capacity considerations, the underlying mathematical framework and symbol definitions (e.g., "Dynamic demand from customer point i at time period t" as defined in TABLE II) confirm the model's inherent adaptability and capacity for dynamic analysis. For more complex, larger-scale, or dynamic urban logistics scenarios, the realism and efficacy of the model could be significantly enhanced by explicitly incorporating time windows for deliveries, more nuanced considerations of dynamic locker capacity, and sophisticated dynamic demand forecasting methodologies. Future research could also benefit from a more comprehensive consideration of additional influencing factors and an analysis of how future population, demand, and traffic conditions might evolve within the target area.

B. *Limited Scope and Generalizability*

While the empirical validation derived from the single university campus case study provides concrete evidence of the model's feasibility in a controlled environment, it is important to acknowledge the inherent limitations regarding its broader applicability. University campuses typically feature concentrated and relatively predictable population and demand patterns, which distinctively contrast with the more heterogeneous and dynamic characteristics of urban residential or commercial areas. The current methodology, in its presented form, does not extensively elaborate on the specific adaptations required to scale or transpose this approach to diverse urban settings or alternative commercial logistics networks. Future research should explicitly address these limitations by developing systematic guidelines for adapting the model's parameters and constraints to varying population distributions, fluctuating demand profiles, and complex traffic conditions prevalent in broader urban environments. This would involve exploring how the core coverage-based methodology could be refined to accommodate the intricacies of metropolitan logistics, thereby enhancing its generalizability and practical utility beyond specialized closed environments.

C. Prospects for work

In this paper, in the process of constructing the site selection model of express pick-up cabinet placement, the exploration of the use of relevant site optimization theory and method, taking into account many aspects of the factors. The outlook of this paper summarises the following points.

(1) This paper selected the four main factors affecting the location of the express pick-up cabinet for hierarchical analysis model research, hope that in future research can be more comprehensive consideration of other factors in the real situation, to further optimize the location of the express pick-up cabinet model.

(2) This paper is based on the current situation of Southwest Jiaotong University Xipu Campus as an empirical research object, hoping that in the future research can fully consider the future population, demand and traffic conditions and other factors in the target area of the development of changes, to further optimise the site selection scheme.

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APPENDIX

CALCULATION RESULTS

Metric / Variable	Value	Reduced Cost / Right Hand Side	Slack or Surplus	Dual Price

Metric / Variable	Value	Reduced Cost / Right Hand Side	Slack or Surplus	Dual Price
Global optimal solution found.				
Objective value	248.0000			
Extended solver steps	0			
Total solver iterations	36			
Variable Values				
N	5.000000	0.000000		
U(1)	0.000000	0.000000		
U(2)	3.000000	0.000000		
U(3)	1.000000	0.000000		
U(4)	2.000000	0.000000		
U(5)	0.000000	0.000000		
DIST Values				
DIST (1, 1)	0.000000	0.000000		
DIST (1, 2)	70.00000	0.000000		
DIST (1, 3)	115.0000	0.000000		
DIST (1, 4)	90.00000	0.000000		
DIST (1, 5)	95.00000	0.000000		
DIST (2, 1)	70.00000	0.000000		
DIST (2, 2)	0.000000	0.000000		
DIST (2, 3)	46.00000	0.000000		
DIST (2, 4)	21.00000	0.000000		
DIST (2, 5)	50.00000	0.000000		
DIST (3, 1)	115.0000	0.000000		
DIST (3, 2)	46.00000	0.000000		

Metric / Variable	Value	Reduced Cost / Right Hand Side	Slack or Surplus	Dual Price
DIST (3, 3)	0.000000	0.000000		
DIST (3, 4)	30.00000	0.000000		
DIST (3, 5)	32.00000	0.000000		
DIST (4, 1)	90.00000	0.000000		
DIST (4, 2)	21.00000	0.000000		
DIST (4, 3)	30.00000	0.000000		
DIST (4, 4)	0.000000	0.000000		
DIST (4, 5)	48.00000	0.000000		
DIST (5, 1)	95.00000	0.000000		
DIST (5, 2)	50.00000	0.000000		
DIST (5, 3)	32.00000	0.000000		
DIST (5, 4)	48.00000	0.000000		
DIST (5, 5)	0.000000	0.000000		
X Values				
X (1, 1)	0.000000	0.000000		
X (1, 2)	0.000000	70.00000		
X (1, 3)	0.000000	115.0000		
X (1, 4)	0.000000	90.00000		
X (1, 5)	1.000000	95.00000		
X (2, 1)	1.000000	70.00000		
X (2, 2)	0.000000	0.000000		
X (2, 3)	0.000000	46.00000		
X (2, 4)	0.000000	21.00000		
X (2, 5)	0.000000	50.00000		
X (3, 1)	0.000000	115.0000		
X (3, 2)	0.000000	46.00000		

Metric / Variable	Value	Reduced Cost / Right Hand Side	Slack or Surplus	Dual Price
X (3, 3)	0.000000	0.000000		
X (3, 4)	1.000000	30.00000		
X (3, 5)	0.000000	32.00000		
X (4, 1)	0.000000	90.00000		
X (4, 2)	1.000000	21.00000		
X (4, 3)	0.000000	30.00000		
X (4, 4)	0.000000	0.000000		
X (4, 5)	0.000000	48.00000		
X (5, 1)	0.000000	95.00000		
X (5, 2)	0.000000	50.00000		
X (5, 3)	1.000000	32.00000		
X (5, 4)	0.000000	48.00000		
X (5, 5)	0.000000	0.000000		
Row Information				
Row 1			0.000000	0.000000
Row 2			248.0000	-1.000000
Row 3			0.000000	0.000000
Row 4			0.000000	0.000000
Row 5			0.000000	0.000000
Row 6			0.000000	0.000000
Row 7			0.000000	0.000000
Row 8			0.000000	0.000000
Row 9			0.000000	0.000000
Row 10			0.000000	0.000000
Row 11			0.000000	0.000000
Row 12			0.000000	0.000000

Metric / Variable	Value	Reduced Cost / Right Hand Side	Slack or Surplus	Dual Price
Row 13			2.000000	0.000000
Row 14			3.000000	0.000000
Row 15			1.000000	0.000000
Row 16			6.000000	0.000000
Row 17			0.000000	0.000000
Row 18			3.000000	0.000000
Row 19			0.000000	0.000000