Spatio-temporal Differentiation and Driving Factors of Low-altitude Logistics Development Level in the Yangtze River Economic Belt

Yantong Chen

Nanjing University of Finance and Economics, Nanjing 210023, Jiangsu, China

Abstract: Using 11 provinces and municipalities along the Yangtze River Economic Belt from 2018 to 2023 as a sample, this study establishes an evaluation system for low-altitude logistics development levels and employs methods such as kernel density estimation, QAP, Markov chains, and Moran's I to examine their spatiotemporal differentiation and evolutionary mechanisms. The findings reveal that while regional development levels have generally improved, the gradient pattern of "downstream leadership, midstream catch-up, and upstream lag" remains stable, with disparities primarily stemming from inter-regional development gaps. The uneven allocation of key factors — including digital infrastructure and aviation logistics capabilities — is the core driver of persistent disparities. Low-altitude logistics development exhibits distinct path dependence and spatial clustering characteristics. These conclusions provide policy recommendations for coordinated low-altitude logistics planning across the Yangtze River Economic Belt.

***Keywords*:** low-altitude logistics, Yangtze River economic belt, spatial differentiation, spatiotemporal disparity

1. Introduction

As a strategic emerging industry, the low-altitude economy is increasingly becoming a new growth driver for regional innovation and development. Among these, low-altitude logistics, driven by strong demand and clear application scenarios, has become the most representative core scenario of the low-altitude economy. It can effectively overcome spatial constraints such as mountainous terrain and water networks, offering distinct advantages in improving delivery efficiency and promoting green transformation, and vividly reflects the practical implementation capabilities of the low-altitude economy.

The Yangtze River Economic Belt spans eastern, central, and western China, where significant disparities in economic foundations and industrial agglomeration have created a typical gradient disparity[1]. This spatial heterogeneity not only constrains traditional logistics but also provides diverse application scenarios for low-altitude logistics, making it an ideal case study for examining regional spatiotemporal differentiation[2]. However, existing studies mostly remain at the macro level and have not effectively delved into specific low-altitude logistics scenarios, making it difficult to capture their unique dependence on the drone industry and takeoff/landing facilities; simultaneously, systematic examinations of the gradient structure of the Yangtze River Economic Belt and the identification of the mechanisms underlying these disparities remain insufficient

To address this, this paper selects the 11 provinces and municipalities of the Yangtze River Economic Belt from 2018 to 2023 as a sample, constructs a dedicated evaluation system, and conducts a systematic analysis by comprehensively applying methods such as the entropy weighting method, the Gini coefficient[3], QAP[4], Markov chains[5], and Moran's I[6]. The marginal contributions are as follows: first, it focuses on specific scenarios to broaden the scope of research; second, it goes beyond static measurements to systematically examine the sources of disparities and their spatial evolution; and third, it reveals the underlying logic of the region's gradient differentiation pattern.

2. Research design

2.1 Construction of the evaluation indicator system for low-altitude logistics development levels

2.1.1 Basis for indicator selection and explanation of measurement logic

Low-altitude logistics is highly dependent on specific technological and infrastructural contexts, making it difficult to characterize directly using traditional logistics metrics. Due to the lack of direct statistical data, this study adheres to the principle of availability and constructs an evaluation system based on four dimensions: foundational support, industrial environment, market demand, and innovation safeguards. Additionally, two core proxy indicators — "number of certified airports" and "number of enterprises holding patents involving drones" — are specifically introduced to accurately capture the unique characteristics of low-altitude logistics.

2.1.2 Construction of the indicator system

This paper constructs a low-altitude logistics evaluation system comprising 4 primary indicators and 12 secondary indicators. Long-distance optical cables, civil aviation cargo volume, and the number of airports reflect infrastructure support[7]; transportation scale, aviation employment, and the number of enterprises holding drone patents characterize industrial capacity; cargo and express delivery turnover measures market demand[8]; and R&D, economic, and fiscal indicators highlight innovation safeguards. This approach comprehensively depicts the region's overall development potential.

Table 1. Evaluation Indicator System for Low-Altitude Logistics Levels in the Yangtze River Economic Belt

Primary Indicators	Second-Level Indicators	Unit	Direction
Basic Supporting Conditions	C1: Length of long-haul optical cable lines	kilometers	+
	C2: Civil Air Cargo Volume	10,000 tons	+
	C3: Number of certified airports	units	+
Industrial carrying capacity	C4: Value added in transportation, warehousing, and postal services	billion yuan	+
	C5: Number of corporate entities in the transportation, warehousing, and postal services sector	units	+
	C6: Number of employees in the air transport industry	persons	+
	C7: Number of companies holding patents related to drones	companies	+
Market Demand Basis	C8: Freight turnover	100 million ton-kilometers	+
	C9:Express Delivery Volume	10,000 pieces	+
Innovation Support Environment	C10: Internal R&D Expenditures	10,000 yuan	+
	C11: Per Capita Regional Gross Domestic Product	yuan	+
	C12: Local general budget expenditures	100 million yuan	+

2.2 Research methods

Comprehensive Evaluation Method: The entropy weighting method was employed to objectively assign weights based on data variability, calculating comprehensive scores for low-altitude logistics development across provinces and cities to eliminate subjective weighting biases. Difference Decomposition Method: The Gini coefficient and its decomposition method were introduced to measure overall differences and break them down into intra-group differences, inter-group net differences, and hypervariability density, thereby accurately identifying the structural sources of regional imbalances and instances of cross-overlap; Identification of Driving Factors: The QAP correlation analysis method was applied. By constructing matrices of absolute inter-provincial indicator differences and composite score , permutation tests were used to identify key factors causing development disparities among regions; Estimation of Distribution Dynamics: Gaussian kernel density estimation was employed to characterize the spatiotemporal evolution of development levels across the entire basin and sub-regions through shifts in location, broadening of distribution, and changes in peak values;Evolutionary trend analysis: Constructing a traditional Markov chain transition matrix , classifying development levels into four tiers (I–IV), and identifying path dependence, locking characteristics, and state transition patterns through the calculation of one-step transition probabilities.

Measurement of Spatial Correlation: Moran's I index was used to test for spatial autocorrelation[9] , and Moran's scatter plots were used to identify four spatial correlation patterns — HH, LL, HL, and LH — to analyze the impact of the neighborhood environment on the agglomeration patterns of regional low-altitude logistics.

2.3 Data sources

Given that drone logistics entered a standardized pilot phase in 2018, providing a data foundation for establishing stable statistical criteria and interprovincial comparative research, this study covers the period from 2018 to 2023. Data were sourced from national, provincial, and municipal Statistical Yearbooks and the EPS platform; missing values were log-transformed and imputed using linear interpolation.

3. Measurement of low-Altitude logistics development levels, regional disparities, and analysis of driving factors in the yangtze river economic belt

3.1 Analysis of measurement results for the development level of low-altitude logistics

There are significant interprovincial differences in the development level of low-altitude logistics in the Yangtze River Economic Belt; the measurement results are shown in Table 2. According to the results calculated using the entropy weighting method, the development level of low-altitude logistics in the Yangtze River Economic Belt generally continued to improve from 2018 to 2023, but a distinct regional gradient emerged, forming a relatively stable pattern characterized by "the downstream leading, the midstream following, and the upstream lagging behind."[10]

From a provincial spatial perspective, low-altitude logistics in the Yangtze River Economic Belt exhibit a significant and stable gradient stratification. The downstream regions of Jiangsu, Zhejiang, and Shanghai have long held the top three positions, forming a high-level agglomeration core. Their leading advantage stems from three factors: first, a concentration of digital and aviation hub resources (such as Pudong and Lukou airports); second, a high concentration of logistics and drone industry players; and third, strong demand for high-efficiency scenarios such as on-demand delivery. Notably, Sichuan has consistently ranked fourth among the upstream regions (with an average of 0.226), achieving a "breakthrough as an isolated region." This is attributable to the aviation support provided by Chengdu Shuangliu and Tianfu's dual airports, as well as its differentiated drone industry foundation. In contrast, Guizhou and Chongqing have long remained at the bottom of the rankings due to shortcomings in infrastructure and market density. From a temporal trend perspective, the overall average fluctuated upward from 0.180 to 0.229 between 2018 and 2023, showing a fluctuating upward trajectory. By region, the downstream sector has consistently maintained a high level and accumulated advantages; the midstream sector has shown strong momentum in catching up (e.g., Hunan's growth rate reached 35.7%); while the upstream sector has improved, the growth remains limited — for instance, Guizhou's absolute level has never exceeded 0.07, and the region as a whole remains in a low-level climbing phase.

3.2 Analysis of Regional Disparities

The results of the Gini coefficient decomposition indicate that,between 2018 and 2023, the inter-group Gini coefficient consistently dominated, remaining stable over the long term between 0.25 and 0.30 — far higher than the intra-group Gini coefficient (0.05–0.09) and the hyper-variation density Gini coefficient (0.03–0.05). This indicates that the primary source of spatial differentiation in low-altitude logistics within the Yangtze River Economic Belt stems from inter-regional disparities rather than intra-regional fragmentation. Both the intra-block Gini coefficient and the super-variable density Gini coefficient have remained at low levels over the long term and show an overall trend of convergence, further illustrating that the internal structures of each block are tending toward stability, and that the phenomenon of cross-regional "late-comer overtaking" is extremely limited. Delving into the underlying mechanisms, low-altitude logistics is constrained by the synergistic interplay of multiple systemic factors — including digital connectivity, industrial agglomeration, professional operations, and market demand — and cannot be rapidly achieved through a single input. The core contradiction in current regional coordination lies in the systemic asymmetry of key development conditions across economic zones, which is also the practical bottleneck that must be resolved to advance gradient transmission and coordinated development.

Analysis of the inter-group Gini coefficient (Figure 1) indicates that regional disparities in low-altitude logistics within the Yangtze River Economic Belt primarily manifest as a development gap between the downstream and the mid-to-upstream regions. The disparity between the upstream and downstream regions is the most pronounced, followed by that between the midstream and downstream regions, with both remaining at high levels over the long term; the disparity between the upstream and midstream regions is relatively smaller and shows a fluctuating downward trend, with the two sectors exhibiting a certain degree of convergence. The downstream region has taken the lead in establishing a comprehensive competitive advantage by leveraging its well-developed digital infrastructure, high-density enterprise clusters, mature market demand, and robust economic foundation, while the middle and upper reaches remain in a catch-up phase overall. The core contradiction underlying the current regional imbalance lies in the systemic asymmetry in the capacity to allocate key factors, which is also the key focus for advancing cross-regional coordination and gradient transmission.

To explore the formation mechanisms of regional disparities in depth, the QAP method was employed for analysis (Table 2). The results indicate that disparities between different segments are driven by different factors, revealing a distinct heterogeneous driving structure. On the one hand, the leading advantage of the downstream segment is the result of the synergy of multiple factors. The disparity between the downstream and midstream regions is primarily driven by per capita GDP, civil aviation cargo volume, aviation talent, and digital infrastructure; whereas the gap between the downstream and upstream regions is dominated by civil aviation cargo volume, freight turnover, per capita GDP, and fiscal expenditure, highlighting the core disparities in modern logistics systems and public investment. On the other hand, the driving logic behind the gap between the middle and upstream tiers is entirely different. This set of differences is significantly driven by the number of drone patent-holding enterprises (0.849***), local fiscal expenditure (0.863***), and express delivery volume (0.658***), while macroeconomic indicators are not significant. This reveals a key industrial logic: the tiered differentiation between the middle and upper tiers does not stem from disparities in overall economic development stages, but rather from the structural consequences of uneven allocation of specific factors — namely, the upper tier's lack of drone innovation clusters, supporting fiscal safeguards, and last-mile delivery markets that have already formed in the middle tier.

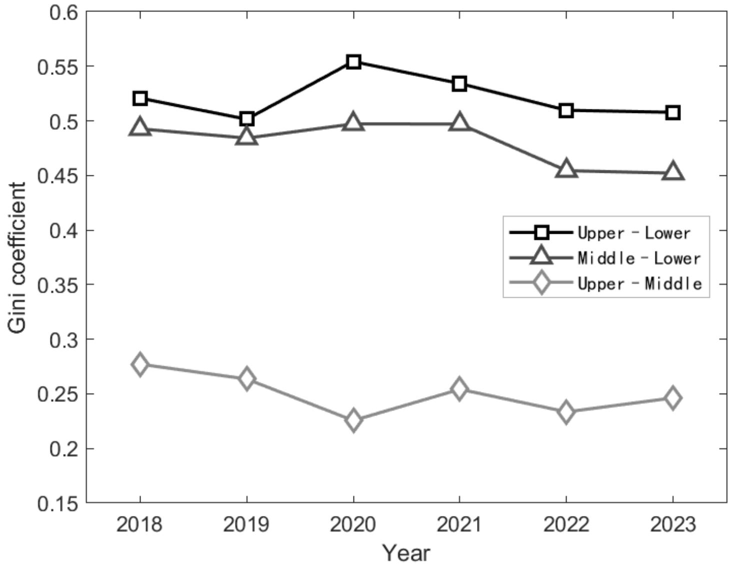

Figure 1. Gini Coefficients Among Regional Groups

Table 2. QAP Results

Variables	Downstream-Midstream Differences	Downstream-Upstream Difference	Midstream-Upstream Difference
C1	0.428* (0.077)	-0.094 (0.694)	0.377 (0.211)
C2	0.531** (0.029)	0.520** (0.013)	0.763 (0.116)
C3	0.328 (0.123)	-0.039 (0.864)	0.249 (0.340)
C4	0.082 (0.670)	0.257 (0.173)	0.468** (0.030)
C5	0.064 (0.721)	0.210 (0.248)	0.250 (0.385)
C6	0.579*** (0.002)	0.358 (0.118)	0.517 (0.130)
C7	0.602*** (0.005)	0.642*** (0.005)	-0.106 (0.717)
C8	0.165 (0.439)	0.254 (0.159)	0.849*** (0.002)
C9	0.102 (0.654)	0.164 (0.357)	0.658*** (0.003)
C10	0.179 (0.384)	0.275 (0.161)	-0.001 (0.997)
C11	0.925*** (0.001)	0.835*** (0.002)	-0.183 (0.533)
C12	0.239 (0.246)	0.389** (0.050)	0.863*** (0.003)

Note: Coefficients are presented in standardized form; p-values are shown in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively

4. Analysis of the Characteristics of Low-Altitude Logistics Development in the Yangtze River Economic Belt

4.1 Analysis of the Spatial Dynamic Distribution Characteristics of Low-Altitude Logistics Development Levels in the Yangtze River Economic Belt

Kernel density estimation results show (Figure 2) that the development level of low-altitude logistics in the Yangtze

River Economic Belt generally continued to rise from 2018 to 2023; however, the decline in peak height and the divergence in peak positions indicate that the gradient stratification pattern remains solid. By sub-region: the downstream region has remained at a high level with its center of gravity continuously shifting to the right, continuously strengthening its accumulated advantages through a positive cycle of "technology — enterprises — scenarios — capital";the midstream region's peak has steadily shifted to the right, indicating it is in a phase of continuous catch-up, though it has not yet surpassed the high-level threshold of the downstream region; the upstream region exhibits high volatility and multi-peak polarization, with development heavily reliant on the driving force of a single core in Sichuan, while provinces such as Yunnan and Guizhou remain stuck in the low-value range for an extended period, making it difficult for the region as a whole to achieve a significant leap forward.

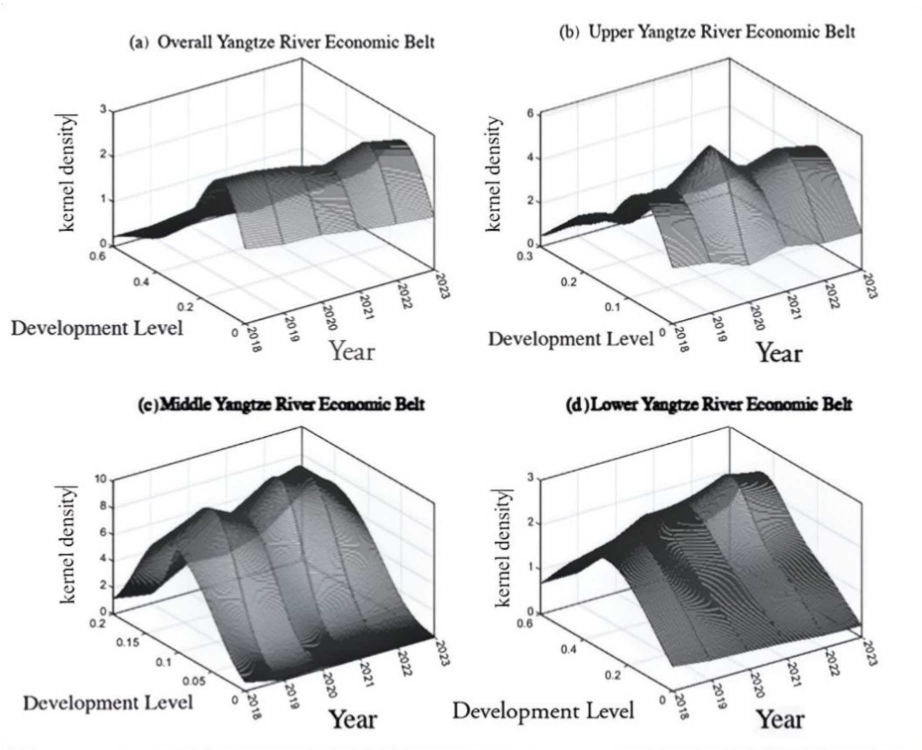

Figure 2. Kernel Density Estimation of Low-Altitude Logistics Development Levels for the Yangtze River Economic Belt as a Whole and Its Upper, Middle, and Lower Reaches

4.2 Analysis of State Transitions and Path Dependence in the Development of Low-Altitude Logistics in the Yangtze River Economic Belt

4.2.1 Characteristics of Temporal Evolution

Analysis based on traditional Markov chain transition matrices (Table 3) indicates that the development level of low-altitude logistics in the Yangtze River Economic Belt exhibits significant temporal inertia and strong "hierarchical stickiness." In terms of state stability, regional evolution displays a typical dynamic pattern of "solidification at both ends and adjustment in the middle."Specifically, the probability of high-level regions (Category IV) maintaining their current state remains consistently at 1.000, indicating that once they establish systemic advantages in digital infrastructure, specialized talent, and industrial agglomeration, they can sustain their leading position through a positive cycle of factors. Conversely, low-level regions (Category I), due to their weak foundations and limited operational support capabilities, have a maintenance probability as high as 0.867, making it extremely difficult for them to achieve a leap forward in the short term.In contrast, regions in the middle tier (Categories II and III), which possess a certain foundation but have not yet formed absolute advantages, exhibit greater transitional dynamics and activity. They are highly susceptible to state transitions under policy support and industrial development. In summary, the tier differences in low-altitude logistics within the Yangtze River Economic Belt are not the result of universal synchronous upgrades or random fluctuations, but rather an inevitable outcome of the long-term asymmetric accumulation of key development conditions and resource factors.

Table 3. Time Markov Chain Results

Time Period	I II III IV	Observed Values
Overall	0.867 0.133 0.000 0.000	15
	0.000 0.786 0.214 0.000	14
	0.000 0.000 0.917 0.083	12
	0.000 0.000 0.000 1.000	14
2018–2020	0.875 0.125 0.000 0.000	8
	0.000 0.800 0.200 0.000	5
	0.000 0.000 0.750 0.250	4
	0.000 0.000 0.000 1.000	5
2021–2023	1.000 0.000 0.000 0.000	4
	0.000 0.833 0.167 0.000	6
	0.000 0.000 1.000 0.000	6
	0.000 0.000 0.000 1.000	6

4.2.2 Spatial Aggregation and Neighborhood Correlation Characteristics

Global Moran's I analysis indicates (Figure 3) that low-altitude logistics in the Yangtze River Economic Belt exhibited significant and stable positive spatial correlation from 2018 to 2023, with agglomeration characteristics further intensifying after 2020. Taking 2023 as an example: the downstream regions of Jiangsu, Zhejiang, and Shanghai remained firmly in the high-high agglomeration zone, forming a core growth pole; the upstream regions of Yunnan, Guizhou, and Sichuan were deeply entrenched in a contiguous low-low lagging zone; and Anhui, driven by the downstream regions, was located in the low-high quadrant. This spatial consolidation pattern stems from the cumulative allocation of key factors along regional tiers — the downstream region has formed a coupling advantage through its comprehensive lead in infrastructure, industry, and markets, continuously reinforcing itself, while the upstream region has fallen into a path lock-in due to topographical constraints and weak industrial support. It is evident that advancing regional synergy hinges not only on raising the absolute level of individual provinces but also on unblocking the chain of factor transmission that allows high-level core areas to spread to surrounding hinterlands.

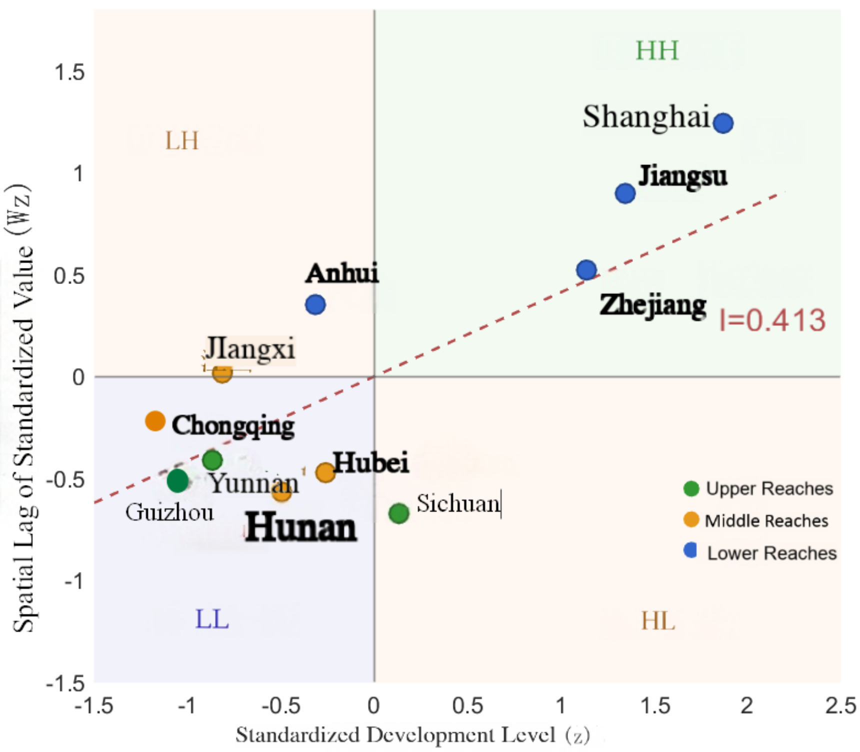

Figure 3. 2023 Moran's I Scatter Plot

5. Conclusions and Implications

The findings indicate that while the overall level of low-altitude logistics in the Yangtze River Economic Belt continued to improve from 2018 to 2023, the gradient pattern of "downstream leading, midstream following, and upstream lagging" remained highly stable. Regional disparities primarily stem from disparities in development levels between sub-regions, and the driving mechanisms exhibit significant heterogeneity: the absolute lead in the downstream is driven by economic development levels and air logistics, while the divergence in the middle and upper reaches is constrained by the presence of drone industry players, fiscal support, and last-mile market allocation. At the same time, regional evolution exhibits strong path dependence and spatial agglomeration characteristics: the "high-high" agglomeration in the downstream region continuously reinforces itself, while the upstream region remains deeply entrenched in a "low-low" lock-in. The asymmetry of spatial spillover effects is the core mechanism exacerbating regional solidification.

Based on this, three key policy implications are proposed: First, implement a "zoning and categorization" approach. The downstream sector should lead in standard-setting and network spillovers, the midstream should accelerate the transformation of hub nodes, and the upstream should achieve industrial breakthroughs by leveraging distinctive scenarios such as mountainous terrain and emergency response. Second, precisely address regional bottlenecks. Bridging the gap between the downstream and the mid-to-upstream sectors requires significantly strengthening modern logistics systems such as air cargo transport; resolving disparities in the mid-to-upstream sectors necessitates shifting the focus to general aviation airport construction, drone R&D and cultivation, and fiscal support for foundational service infrastructure. Third, promote the "institutionalization" of spatial spillover. Relying on the Yangtze River trunk line, jointly build cross-provincial cooperation corridors, establish a targeted output mechanism where "advanced regions lead less developed ones," and set up regional coordination platforms in core cities to thoroughly break down geographical barriers and low-level lock-in through institutional synergy.

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Author Bio

Yantong Chen (born in 2002), Female, Han, Jiangsu, Master's, Research Focus: Logistics Management