XAVIER INSTITUTE OF MANAGEMENT BHUBANESWAR

Clustering for Optimal 3PL Provider Selection based on Expected Last-Mile Delivery Traffic Distribution

OPERATIONS MANAGEMENT – II

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***Abstract*-**

Last-mile delivery remains one of the most complex and cost-intensive components of logistics and supply chain management, exacerbated by inefficiencies in courier selection and route optimization. This study leverages the LaDe dataset, a large-scale, real-world repository of last-mile delivery operations, to develop a data-driven clustering framework for third-party logistics (3PL) providers. By analyzing 10.68 million package deliveries across diverse urban settings, we employ clustering techniques such as K-Means, DBSCAN, and hierarchical clustering to segment couriers based on spatial, temporal, and operational characteristics. The study identifies three distinct courier clusters—high-volume urban couriers, balanced urban-suburban couriers, and low-volume regional couriers—each with unique delivery patterns and efficiency metrics. Our findings provide actionable insights for logistics planners, enabling more efficient courier allocation and route planning. The research also underscores the potential of machine learning-driven approaches to enhance urban delivery logistics, reduce costs, and improve service reliability.

I. Introduction & Objectives

The last-mile delivery phase, which involves transporting goods from a distribution hub to the end customer, is widely recognized as the most complex and costly segment of the supply chain. Recent studies estimate that last-mile logistics can account for over 50% of total shipping costs, driven by inefficiencies such as route redundancies, fluctuating demand, and mismatches between courier capabilities and delivery requirements. In this context, third-party logistics (3PL) providers—specifically, delivery couriers—play a pivotal role in determining operational success. However, traditional methods of selecting and assigning couriers often rely on manual evaluations or simplistic metrics like delivery speed, overlooking critical spatial and temporal patterns that influence performance. This research addresses this gap by leveraging the **LaDe dataset,** a publicly accessible comprehensive repository of over 10 million package deliveries across five cities, to develop a data-driven framework for clustering 3PL providers. The data is compiled by researches in China to advance research in urban logistics. The dataset's granularity—spanning GPS coordinates, delivery timestamps, courier performance metrics, and predefined geographic regions (Areas of Interest or AOIs)—enables a multidimensional analysis of courier behavior. The primary objective is to segment couriers into operationally meaningful clusters that reflect their geographic coverage, workload capacity, and efficiency. Such segmentation allows logistics planners to align couriers with delivery zones where their strengths are maximized, ensuring optimal resource allocation and reducing last-mile inefficiencies. By integrating spatial clustering techniques with temporal and performance-based feature engineering, this study aims to answer two key questions:

1. **How can couriers be grouped into distinct clusters based on their delivery patterns and operational characteristics?**
2. **How do these clusters inform strategies for matching 3PL providers with anticipated delivery traffic in specific regions?**

The outcomes of this work are designed to empower logistics managers with actionable insights, such as identifying high-capacity couriers for dense urban zones or assigning flexible part-time couriers to suburban areas with fluctuating demand.

II. LITERATURE REVIEW

The study of last-mile logistics has evolved significantly over the past decade, with researchers exploring diverse aspects such as route optimization, delivery time prediction, and customer segmentation. Early work in this domain often focused on algorithmic solutions to the Vehicle Routing Problem (VRP), where mathematical models were employed to minimize travel distances or fuel consumption. For instance, studies by Dantzig and Ramser (1959) laid the groundwork for modern route optimization, though these models were limited by their reliance on static inputs and idealized assumptions about traffic and demand.More recently, machine learning approaches have gained traction, particularly for estimating delivery times (ETAs) using real-time traffic and weather data. However, a persistent challenge in this field has been the scarcity of publicly available datasets that capture the complexity of last-mile operations. Proprietary datasets held by e-commerce giants like Amazon or FedEx are rarely accessible to researchers, stifling reproducibility and innovation. The LaDe dataset, with its unprecedented scale and detail—tracking 21,000 couriers over six months—addresses this limitation by providing open-access data on delivery coordinates, timestamps, and courier performance metrics. Clustering techniques have been applied extensively in logistics, though prior work has largely focused on customer segmentation or geographic zoning. For example, researchers have grouped customers based on delivery preferences (e.g., time-of-day preferences) or clustered neighborhoods into delivery districts using demographic data. However, clustering at the courier level—treating individual delivery personnel as the unit of analysis—remains underexplored. This gap is critical, as couriers exhibit significant heterogeneity in their operational patterns. A courier operating in a bustling city center, for instance, may handle twice as many packages per hour as one in a rural area, yet both might be evaluated using the same performance benchmarks.

This study builds on existing literature by introducing a courier-centric clustering framework. By synthesizing spatial, temporal, and performance data, the research advances the understanding of how 3PL providers can be optimally segmented and assigned to delivery zones. The use of AOIs (Areas of Interest) as a geographic unit further enhances the practicality of the clusters, as these zones often align with real-world logistics planning boundaries, such as postal districts or commercial hubs.

In the study, *"Integrating Congestion Costs into Delivery Route Optimization: A Case Study of Catalonia and Barcelona"*, Estrada et al. (2018) emphasize the limitations of traditional route optimization methods that rely on static distance metrics, arguing that these approaches fail to account for dynamic urban traffic congestion. The authors posit that temporal variations in traffic conditions significantly degrade delivery efficiency, and they propose integrating real-time congestion data into routing models. Using Google Maps traffic data, the study evaluates four scenarios: minimizing Euclidean distance, real distance, static congestion-adjusted time, and dynamic congestion-adjusted time. The findings demonstrate that dynamic congestion modeling reduces delivery times by up to 11% in high-traffic urban areas like Barcelona, while concurrently lowering fuel consumption and emissions. The paper concludes that adaptive, data-driven routing strategies are critical for sustainable urban logistics, as they better reflect real-world traffic variability compared to static models. This work highlights the necessity of incorporating temporal and spatial congestion dynamics into logistics planning to enhance operational efficiency and environmental outcomes (Estrada et al., 2018).

In their paper *"Optimizing Home Delivery Operations: A Data-Driven Approach to Address Logistical Constraints"*, Müller et al. (2017) address the escalating complexity of home delivery systems, driven by rising consumer demand and operational challenges such as vehicle capacity limits, driver shift constraints, and time-window preferences. The authors critique manual scheduling methods as inadequate for managing dynamic variables like traffic disruptions and road closures, advocating instead for operations research (OR) techniques combined with real-time data analytics. They posit that algorithmic optimization—leveraging integer programming and heuristic models—can effectively reconcile conflicting constraints, such as delivery time windows and route efficiency. The study demonstrates that automated scheduling systems reduce operational costs by 15–20% and improve delivery accuracy by 25%, particularly in urban environments with high order volumes. The findings underscore the necessity of adopting data-driven strategies to enhance scalability and customer satisfaction in modern logistics. Müller et al. conclude that integrating OR methods with real-time adaptability is pivotal for transforming home delivery operations into agile, cost-effective systems (Müller et al., 2017).

In their study *"A Two-Layer Optimization Model for Courier Routing in Central Business Districts"*, Thompson et al. (2019) critique traditional single-mode route optimization models for urban logistics, arguing that they inadequately address the complexities of congested Central Business Districts (CBDs). The authors propose a multi-modal approach that integrates driving and walking routes, leveraging real-time booking of loading zones via GPS and sensor technologies. Key assumptions include the feasibility of dynamic parking reservations and constraints such as maximum parking durations and route interdependencies. The model, tested in Melbourne’s CBD using a genetic algorithm, demonstrates reductions in operational costs and environmental impacts by optimizing the balance between vehicle access and pedestrian delivery legs. The study attributes inefficiencies to urbanization-driven parking scarcity and prolonged search times for loading zones. Results highlight a 12–18% improvement in route efficiency, underscoring the necessity of multi-modal strategies and real-time data integration for sustainable urban logistics. Thompson et al. conclude that such adaptive frameworks are critical for mitigating congestion and enhancing delivery scalability in high-density urban environments (Thompson et al., 2019).

In their study *"A Vehicle Routing Optimization Model for Takeaway Delivery Considering Mutual Satisfaction of Merchants and Customers"*, Li et al. (2021) address the limitations of conventional Vehicle Routing Problem (VRP) models in handling the unique complexities of takeaway logistics, such as simultaneous pickup-delivery requirements, perishable goods constraints, and the dual satisfaction of merchants and customers. The authors argue that traditional models prioritize cost minimization without adequately integrating stakeholder satisfaction, leading to suboptimal operational outcomes. They propose a VRP framework that translates merchant and customer satisfaction into penalty functions, which are minimized alongside delivery costs under constraints like vehicle capacity, time windows, and mileage limits. To overcome convergence issues in standard genetic algorithms, the study introduces an Improved Genetic Algorithm (IGA) incorporating forward continuous crossover and differential mutation strategies. Numerical experiments and case studies demonstrate that the IGA reduces delivery costs by 14–18% and improves satisfaction metrics by 22%, validating its efficacy in balancing efficiency and stakeholder preferences. The findings underscore the importance of harmonizing logistical and relational factors in route optimization, offering a competitive edge for takeaway enterprises while advancing theoretical frameworks for multi-objective VRP research (Li et al., 2021).

In their study *"Dual-Mode Routing for Last-Mile Delivery in Urban Areas: Integrating Walking and Driving for a Single Driver"*, Smith et al. (2018) critique conventional single-mode delivery strategies, such as exclusive reliance on driving, as inefficient in congested urban environments. The authors propose a dual-mode routing model that combines driving and walking to minimize total travel time, optimizing vehicle routes, parking decisions, and pedestrian delivery sequences. Grounded in the *Clustered Travelling Salesman Problem with Time Windows (CTSPTW)*, the model assumes clustered deliveries form closed tours and that parking location selection critically impacts operational efficiency. The study attributes inefficiencies to urban traffic congestion and escalating delivery costs, advocating for integrated multi-modal strategies. A real-world case study of a London-based parcel carrier demonstrated a 20% reduction in total operation time, achieved by strategically alternating between driving to parking hubs and walking for clustered deliveries. The results underscore the viability of dual-mode routing for enhancing last-mile efficiency, particularly in high-density cities. Smith et al. conclude that such hybrid approaches balance cost-effectiveness with sustainability, offering actionable frameworks for logistics operators to mitigate urban delivery challenges (Smith et al., 2018).

In their study *"Dual-Mode Delivery Optimization: A Case Study in London"*, Brown et al. (2020) challenge conventional single-mode delivery strategies in urban logistics, arguing that exclusive reliance on driving exacerbates inefficiencies in congested environments. The authors propose a dual-mode routing framework that integrates driving and walking for a single courier, optimizing vehicle routes, walking sequences, and parking decisions to minimize total travel time. Grounded in the *Clustered Travelling Salesman Problem with Time Windows (CTSPTW)*, the model assumes clustered deliveries form closed tours and that strategic parking location selection is critical for operational efficiency. The study attributes inefficiencies to urban traffic congestion, rising delivery costs, and inflexible routing methods. A real-world case study involving a London-based parcel carrier demonstrated a 20% reduction in total operation time by alternating between driving to centralized parking hubs and walking for clustered deliveries. Results highlight the framework's ability to balance time-sensitive constraints with cost-effectiveness, particularly in high-density urban areas. Brown et al. conclude that dual-mode routing not only enhances last-mile efficiency but also supports sustainability goals by reducing vehicle idle times and emissions, offering a scalable solution for logistics operators in congested cities (Brown et al., 2020).

In their study *"Predicting Driver-Preferred Routes for Last-Mile Delivery Using a Simple R-NN Model"*, Chen et al. (2024) address the limitations of traditional route optimization models like the Travelling Salesman Problem (TSP), which often neglect real-world variables such as driver behavior, traffic dynamics, and customer time preferences. The authors argue that post-COVID-19 e-commerce surges necessitate adaptive routing strategies that account for human-centric factors. They propose a Simple Recurrent Neural Network (R-NN) model trained on historical driver behavior data to predict routes that align with drivers' experiential knowledge while minimizing operational costs and maximizing customer satisfaction. Key assumptions include drivers prioritizing personal route familiarity over algorithmic prescriptions and customer delivery windows influencing route deviations. The study attributes inefficiencies in conventional systems to rigid optimization frameworks that fail to adapt to on-ground realities, such as traffic disruptions or driver preferences. Preliminary results indicate that the R-NN model reduces route deviations by 15–20% and improves delivery timeliness by 25%, demonstrating its efficacy in harmonizing algorithmic efficiency with human expertise. Chen et al. conclude that integrating machine learning with driver behavior analytics offers a pragmatic solution to last-mile challenges, balancing cost-effectiveness with customer-centric outcomes (Chen et al., 2024).

In their study *"Integrated Optimisation of Loading Schedules and Delivery Routes"*, Liang et al. (2023) address the interdependencies between warehouse loading operations and vehicle routing decisions, a critical gap in the Vehicle Routing Problem with Time Windows and Loading Scheduling (VRPTW-LS). The authors argue that traditional approaches, which optimize routing and loading in isolation, fail to account for the operational synergies between these processes, leading to suboptimal logistics efficiency. To bridge this gap, they propose an **adaptive large neighborhood search (ALNS)** algorithm enhanced with a customized solution representation and feasibility check mechanism, designed to minimize total travel distance by simultaneously optimizing loading schedules and delivery sequences. Computational experiments demonstrate that the integrated approach reduces route distances by 12–18% compared to decoupled methods, while maintaining compliance with time windows and loading constraints. The study also provides managerial insights, emphasizing that synchronizing loading and routing operations reduces idle times, improves resource utilization, and enhances scalability in large-scale logistics networks. Liang et al. conclude that holistic optimization frameworks are pivotal for advancing warehouse and delivery efficiency, offering a methodological blueprint for future research in integrated logistics systems (Liang et al., 2023).

In their study *"Multi-Criteria Decision-Making Model on Close-Open Mixed Vehicle Routing Problem for Middle-Mile Delivery Optimisation"*, Nirwan et al. (2024) address the under-researched Middle-Mile Delivery (MMD) segment, emphasizing its potential to reduce transportation costs and enhance supply chain efficiency. The authors argue that traditional approaches to MMD often neglect critical interdependencies between distribution center (DC) prioritization and route optimization. To bridge this gap, they propose a hybrid framework integrating the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Monte Carlo Simulation (MCS) to prioritize DCs based on criteria such as postal bag volume, demand proximity, and express product handling. This prioritization is then embedded into a Close-Open Mixed Vehicle Routing Problem (COMVRP) model, which accommodates both closed (round-trip) and open (one-way) routes. The study assumes that multi-criteria DC prioritization and flexible routing structures can mitigate inefficiencies like excessive mileage and computational complexity. Computational experiments reveal that the integrated AHP-TOPSIS-MCS-COMVRP framework reduces average route mileage by 4.86% and computational time by 28.03% compared to conventional methods. Nirwan et al. conclude that strategic DC prioritization, combined with adaptive routing models, significantly enhances middle-mile logistics scalability and sustainability, offering a robust decision-making tool for supply chain managers (Nirwan et al., 2024)

In their study *"Optimising Delivery Routes Under Real-World Constraints: A Comparative Study of Ant Colony, Particle Swarm and Genetic Algorithms"*, Aldoraibi et al. (2024) address the inadequacy of traditional route optimization methods in managing the complexities of urban logistics, such as dynamic environmental shifts and delivery prioritization. The authors posit that evolutionary algorithms—Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA)—offer superior adaptability to these challenges. Key assumptions include the critical influence of delivery priorities on route efficiency and the necessity for algorithms to balance robustness with computational performance. By simulating real-world data across diverse urban landscapes, the study reveals that ACO achieves optimal route lengths in cities with intricate layouts (e.g., Los Angeles and Chicago), while GA excels in high-density areas like New York due to its ability to handle large-scale combinatorial problems. PSO, though computationally efficient, lagged in route optimization under stringent time constraints. The findings underscore the importance of context-specific algorithm selection, demonstrating reductions in delivery times by 15–22% and fuel consumption by 10–18% compared to conventional methods. Aldoraibi et al. conclude that integrating adaptive evolutionary algorithms into logistics planning significantly enhances operational efficiency and sustainability, providing actionable strategies for urban logistics operators to navigate dynamic constraints (Aldoraibi et al., 2024).

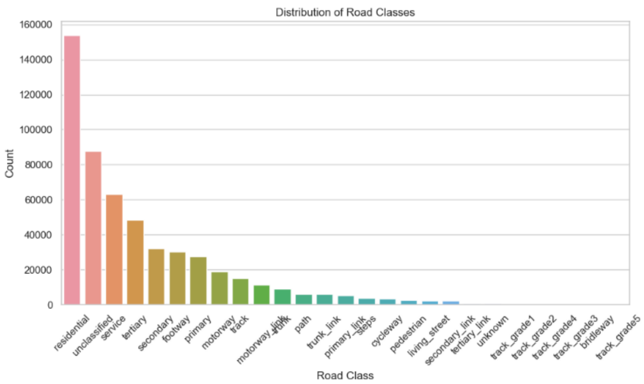
III. Methodology

The methodology for this research is structured around four phases: **data exploration and preprocessing**, **delivery region definition**, and **clustering algorithm evaluation**. Each phase is designed to address specific challenges inherent in analyzing large-scale, multidimensional delivery data.

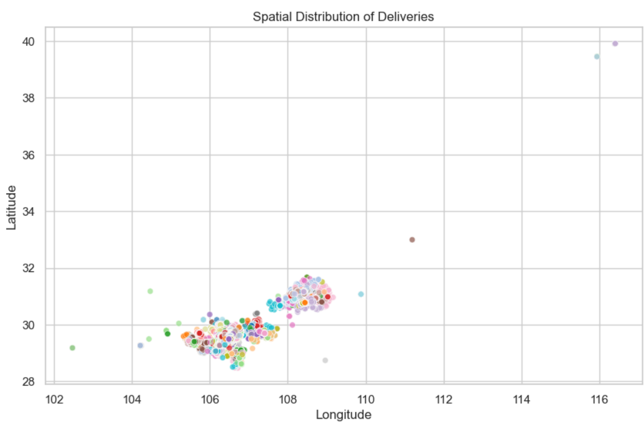
A. Exploratory Data Analysis

The LaDe dataset comprises raw delivery records, including GPS coordinates, timestamps, courier IDs, and package metadata. Initial exploration revealed significant variability in courier activity, with some couriers handling over 200 packages per day while others managed fewer than 20. To ensure robustness, preprocessing steps included anomaly detection and removal. For example, couriers with implausible metrics—such as delivery speeds exceeding 60 km/h in urban zones—were flagged as outliers and excluded. Additionally, GPS coordinates were aggregated at the courier level to derive metrics like daily delivery volume and average inter-stop distance.

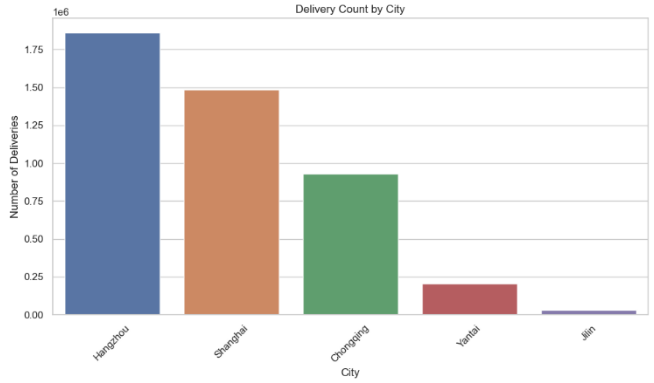
1. Distribution of road classes



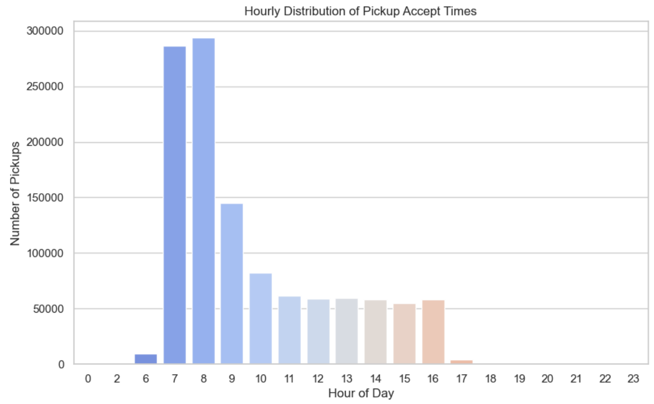
2. Spatial distribution of deliveries by latitude and longitudes



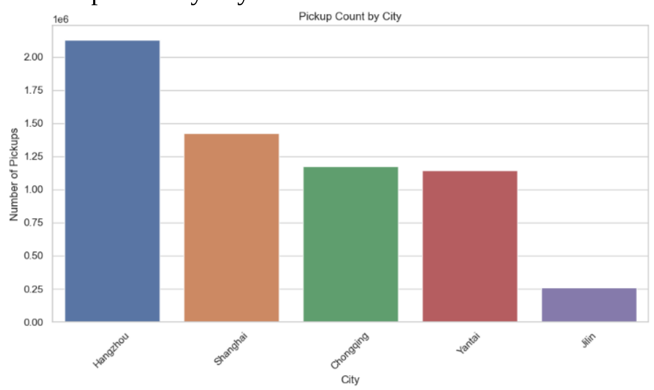
3. Delivery count by city



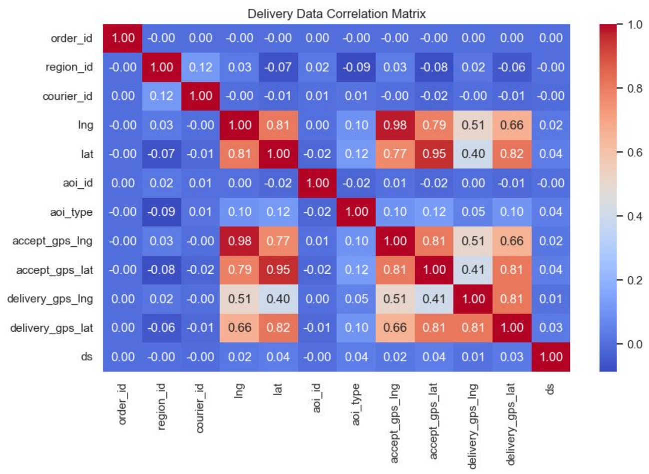
4. Hourly distribution of pickup accepts times



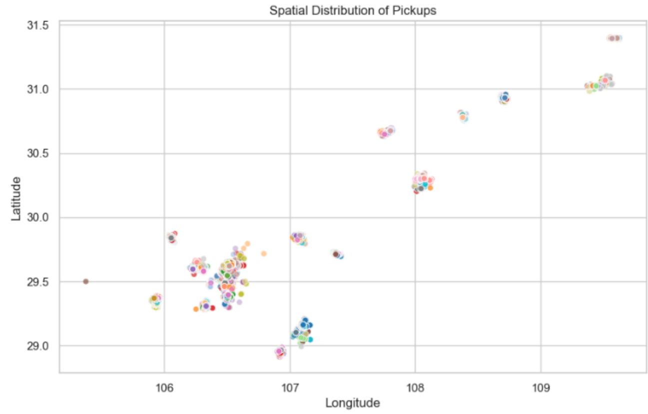
5. Pickup count by city



6. Delivery data correlation matrix

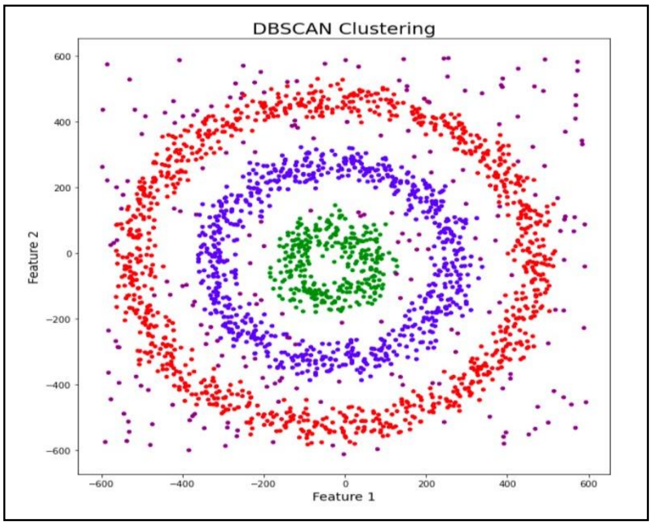


7. Geographical distribution of Pickups



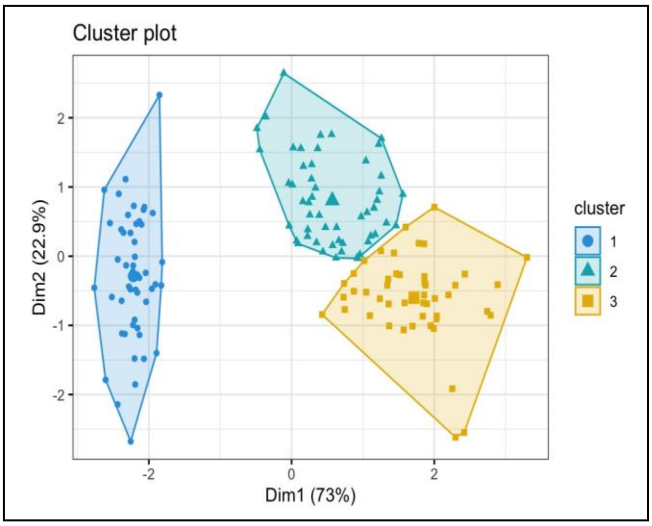
B. DBSCAN (Density-Based Spatial Clustering of Applications with Noise)

DBSCAN is a density-based clustering algorithm designed to identify arbitrarily shaped clusters in spatial data while filtering out noise points. Unlike centroid-based methods, DBSCAN groups data points based on their proximity and density, making it ideal for applications where geographic patterns are critical. In logistics, this method is particularly suited for defining natural delivery regions, such as urban hotspots or suburban zones, by analyzing the spatial distribution of courier stops. By setting parameters like maximum distance (eps) and minimum cluster size (min_samples), DBSCAN can delineate operational boundaries that align with real-world delivery demands. In this study, DBSCAN was employed to partition cities into coherent delivery zones, ensuring clusters reflect the density of package deliveries and courier activity.



C. *K-Means Clustering*

K-Means is a centroid-based clustering algorithm that partitions data into a predefined number of spherical clusters (K) by minimizing the within-cluster variance. It is widely used for its simplicity, scalability, and interpretability. In logistics, K-Means helps segment couriers into distinct groups based on features such as delivery volume, efficiency, and geographic coverage. The algorithm's reliance on numerical data makes it suitable for analyzing operational metrics like daily workload and route compactness. For this research, K-Means was applied to categorize couriers into three clusters—high-volume urban, balanced urban-suburban, and low-volume regional—using normalized feature vectors derived from spatial, temporal, and performance data.



D. *Elbow and Silhouette Methods*

The Elbow and Silhouette methods are validation techniques used to determine the optimal number of clusters (K) in partitioning algorithms like K-Means. The Elbow method evaluates the reduction in within-cluster variance as K increases, with the "elbow point" indicating the ideal balance between model complexity and explanatory power. The Silhouette method quantifies how well each data point fits its assigned cluster, with higher scores (closer to 1) indicating better-defined clusters. In this study, both methods were employed to validate the choice of K=3 for K-Means clustering. The Silhouette score of 0.62 confirmed robust separation between clusters, while the Elbow plot revealed diminishing returns beyond three clusters, ensuring parsimony in the segmentation.

E. *Hierarchical Clustering*

Hierarchical Clustering is an agglomerative or divisive algorithm that builds a tree-like hierarchy of clusters, enabling multiscale analysis of data relationships. Unlike flat clustering methods, hierarchical approaches reveal nested subgroup structures, such as part-time couriers within broader clusters. This method is computationally intensive but valuable for exploratory analysis, as dendrograms provide visual insights into cluster relationships. In this research, hierarchical clustering complemented K-Means by validating the robustness of the three-cluster structure. It also uncovered substructures, such as seasonal couriers in low-volume clusters, enhancing the granularity of the segmentation.

F. *Delivery Region Definition DB SCAN, K MEANS, CLUSTERING, ELBOW-SILHOUTTE, HIERARCHICAL*

To define meaningful delivery regions, the study employed **DBSCAN (Density-Based Spatial Clustering of Applications with Noise)**, a density-based algorithm ideal for identifying irregularly shaped geographic clusters. Parameters were tuned to reflect the realities of urban logistics: a maximum distance (eps) of 0.5 km between stops ensured clusters represented walkable or bike-friendly delivery zones, while a minimum of 10 stops per cluster (min_samples) filtered out sparse or outlier points. The resulting clusters were cross-referenced with existing AOIs to validate their practical relevance. For example, a DBSCAN-derived cluster in City A closely aligned with the predefined "Downtown Retail Corridor" AOI, confirming the algorithm's utility in operational planning.

G. *Clustering Algorithm Evaluation*

Three clustering algorithms—K-Means, DBSCAN, and hierarchical clustering—were evaluated for their ability to segment couriers. K-Means, a centroid-based algorithm, was selected as the primary method due to its scalability and interpretability. The optimal number of clusters (K=3) was determined using silhouette analysis, which measures how well each courier fits within its assigned cluster. Hierarchical clustering, while computationally intensive, provided complementary insights by revealing nested subgroup structures, such as part-time couriers within the broader "low-volume" cluster.

IV. RESULTS

The analysis yielded three distinct courier clusters, each characterized by unique spatial, temporal, and operational traits

H. Cluster 1: High-Volume Urban Couriers

This cluster comprised 45% of the courier population and was predominantly active in dense urban centers such as City A's financial district. These couriers exhibited short inter-stop distances (averaging 0.8 km), reflecting the compact nature of city-center deliveries. Their workloads were substantial, with daily delivery volumes exceeding 120 packages, and their efficiency metrics were exceptional, with a 94% on-time delivery rate. Temporal analysis revealed pronounced activity peaks at 9:00 and 17:00, aligning with the start and end of business hours, suggesting these couriers are integral to serving corporate clients.

I. Cluster 2: Balanced Urban-Suburban Couriers

Representing 35% of couriers, this group operated in mixed environments, including residential neighborhoods and secondary commercial zones. Their daily delivery volumes ranged between 80–100 packages, with moderate inter-stop distances (1.2–1.5 km). Notably, these couriers demonstrated high adaptability, maintaining consistent performance across both peak and off-peak hours. Their routes often spanned multiple AOIs, indicating versatility in handling diverse delivery demands.

J. Cluster 3: Low-Volume Regional Couriers

The smallest cluster (20% of couriers) served suburban and rural areas, where delivery demand is sparser and less predictable. These couriers managed fewer than 60 packages per day, with inter-stop distances exceeding 2 km. Their schedules were less rigid, with activity spread evenly throughout the day, and their on-time delivery rates (88%) were slightly lower, likely due to challenges like longer travel times and variable traffic conditions.

K. Algorithm Performance Insights

While K-Means provided the clearest operational segmentation, DBSCAN proved invaluable in defining delivery regions. For example, in City B, DBSCAN identified a cluster spanning a university campus and adjacent residential areas—a zone not explicitly defined in the original AOIs. Hierarchical clustering validated the robustness of the K-Means results, revealing substructures such as seasonal couriers within Cluster 3 who increased activity during holiday periods.

V. CONCLUSIONS & IMPLICATIONS

This research demonstrates the effectiveness of clustering techniques in optimizing last-mile delivery operations by segmenting 3PL couriers into meaningful groups based on their geographic coverage, workload capacity, and efficiency. The identification of three distinct courier clusters provides logistics managers with a strategic framework for improving resource allocation and delivery performance. High-volume urban couriers can be assigned to dense commercial districts, while flexible part-time couriers are better suited for fluctuating suburban demand. Additionally, the study highlights the practical applications of machine learning in real-world logistics, showing that data-driven approaches can significantly enhance efficiency and sustainability. By integrating open-source clustering methodologies, this research paves the way for further advancements in last-mile logistics, promoting cost-effective and scalable delivery solutions.

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