Optimal Location Policy of Dark Stores for Quick Commerce Companies

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1. Abstract

Quick commerce companies strive to achieve ultra-fast product deliveries, often within hours or less. This delivery model, known for its speed, presents distinct challenges related to the strategic placement of dark stores and the associated delivery costs.

The core objective is to identify clusters of demand points and determine optimal locations for dark stores within these clusters. The goal is to minimize operational costs while maximizing service levels and customer satisfaction across all demand points.

In this project, we approach the problem by formulating it as a mixed integer linear program (MILP) to provide a computational solution. Our aim is to determine the optimal number and locations of dark stores based on existing demand patterns and operational constraints.

2. Literature Review

Finding the ideal location for warehouses and distribution centers is crucial for efficient and cost-effective quick commerce and e-commerce supply chains. This study focuses on a common strategy: using customer demand data to identify strategic warehouse locations.

Clustering network data is fundamental in network analysis, enabling subsequent machine learning tasks such as predictive analytics and group characterization. Despite its computational complexity—often categorized as NP-hard, mixed-integer linear programming (MILP) presents a versatile framework for modeling clustering problems and generating globally optimal solutions [1].

In this context, the model utilized draws inspiration from the work of Nascimento et al. [2], originally devised for biological data analysis. This model has been adapted to identify clusters of demand locations that minimize intra-cluster distances, a crucial criterion for efficient warehouse placement. The subsequent identification of centroids—representing nodes with the minimum aggregate distance to all other nodes within a cluster—provides an effective strategy for determining optimal dark store locations.

By strategically positioning warehouses based on historical demand patterns, the aim is to optimize proximity to customer locations while balancing operational costs.

The relevance of this research extends to the strategic objectives of companies operating in the quick commerce sector, where maximizing profitability hinges on effectively covering all demand points while optimizing operational efficiency.

In summary, this study contributes to the evolving field of supply chain optimization for quick commerce by integrating established clustering methodologies with MILP-based modeling, offering a robust framework for strategically locating dark stores and enhancing overall operational performance.

Here are some relevant sources:

1. "Finding clique clusters with the highest betweenness centrality. European Journal of Operational Research." by Rysz M, Pajouh FM, Pasiliao EL.

2. "Investigation of a new GRASP-based clustering algorithm applied to biological data." by Nascimento MCV, Toledo FMB, de Carvalho ACPLF.

3. "Mixed integer linear programming formulation for K-means clustering problem." by Ágoston, K.C., E.-Nagy, M. (2024).

4. "Optimizing Last Mile Delivery for E-commerce Omni-Channel Retailing: A Facility Location Approach," by Gao et al. (2019)

3. Mathematical formulation and framework

The formulation was divided into two parts. The first part dealt with cluster formation and the second part focused on finding the centroid of the cluster.

1. The method aims to minimize the total distance within the cluster when a set of data points and the number of clusters is provided.

$$\min \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} d_{ij} y_{ij} \tag{1}$$

subject to

$$\sum_{c=1}^{k} x_{ic} = 1, \qquad \forall i \in V \tag{2}$$

$$\sum_{i=1}^{N} x_{ic} \geq 1, \qquad \forall c \in C \tag{3}$$

$$y_{ij} \geq x_{ic} + x_{jc} - 1, \qquad i = 1, \ldots, N-1; j = i+1, \ldots, N; \forall c \in C \tag{4}$$

$$y_{ij} \in \{0, 1\}, \qquad i = 1, \ldots, N-1; j = i+1, \ldots, N \tag{5}$$

$$x_{ic} \in \{0, 1\}, \qquad \forall i \in V, \forall c \in C \tag{6}$$

N is the number of objects to cluster. k is the number of clusters, a user-defined parameter. y_{ij} are binary variables taking value 1 if members i, j are in the same cluster, 0 otherwise. d_{ij} are the distance values between members i, j. The first constraints (2) makes sure that each object is found in exactly one cluster. The second set of constraints avoids empty clusters (3). The third set of constraints (4) is to relate variables to each other in a linear fashion. The last two sets of constraints (5, 6) restrict the domains of variables.

2. Since, now we have the nodes divided into the clusters, we can now find the optimal location of the dark stores within each cluster by finding the centroid of all the available points.

Let $(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$ be n points in a given cluster.

The coordinates of the centroid $(\bar{x}, \bar{y})$ of these points are calculated as:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i$$

The centroid $(\bar{x}, \bar{y})$ represents the optimal location for a dark store within the cluster, as it minimizes the average distance to all points in that cluster. By integrating cluster formation with centroid calculation, this approach enables the strategic placement of dark stores to efficiently serve customer demand while minimizing operational costs.

4. Programming Approach

In this project, we implemented a mathematical optimization model using Python and the PuLP library to solve a graph optimization problem. The goal was to determine the optimal location of dark stores based on given node coordinates and cluster constraints. The code could be found out here

4.1 Solution Approach

To solve the optimization problem, we followed these steps:

1. **Model Formulation**: We defined decision variables (`x` and `y`) to represent node clustering and edge connections, respectively.
2. **Objective Function**: The objective was to minimize the sum of distances between connected nodes (`y[i, j]`).
3. **Constraints**: We imposed constraints to ensure each node is assigned to exactly one cluster (`k`) and enforced cluster connectivity using binary decision variables.

4.2 Implementation Details

- **PuLP Library**: We utilized the PuLP library to construct the MILP model and solve it efficiently.
- **Visualization**: Matplotlib was employed to visualize the optimal dark store locations, node clusters, and inter-cluster connections.
- **Cluster Analysis**: Centroids of each cluster were computed and plotted to represent the central location of dark store clusters.

4.3 Results and Insights

The MILP model successfully determined the optimal dark store locations based on the given constraints and node coordinates. By analyzing the cluster centroids and inter-cluster connections, we gained insights into the spatial distribution and connectivity of the dark store network.

5. Applications

The optimal location policy for dark stores has diverse applications across several sectors, offering tangible benefits in terms of operational efficiency and customer satisfaction. This section explores key application areas where our study's findings can be applied:

5.1 E-commerce and Quick Commerce

In the e-commerce and quick commerce sectors, the strategic placement of dark stores plays a critical role in accelerating delivery times and reducing last-mile costs. By optimizing dark store locations based on demand patterns, companies can enhance order fulfillment and customer experiences.

5.2 Urban Planning and Logistics

Our research findings have implications for urban planning and logistics management. Placing dark stores strategically within urban areas helps alleviate traffic congestion and reduce environmental impact by minimizing delivery distances. This approach aligns with sustainable urban development goals.

5.3 Supply Chain Optimization

Supply chain optimization benefits significantly from optimized dark store locations. By clustering demand points and strategically positioning dark stores, companies can streamline inventory management, reduce transportation costs, and improve supply chain resilience.

5.4 Retail and Consumer Goods

In the retail and consumer goods sectors, dark stores serve as distribution hubs for fulfilling online orders and meeting peak demand. Efficient dark store placement enables retailers to scale their e-commerce operations while maintaining profitability and customer satisfaction.

5.5 Last-Mile Delivery Services

The concept of dark stores is integral to last-mile delivery services, enabling rapid and efficient delivery of goods to end customers. By leveraging data-driven location policies, delivery service providers can optimize delivery routes and minimize delivery times.

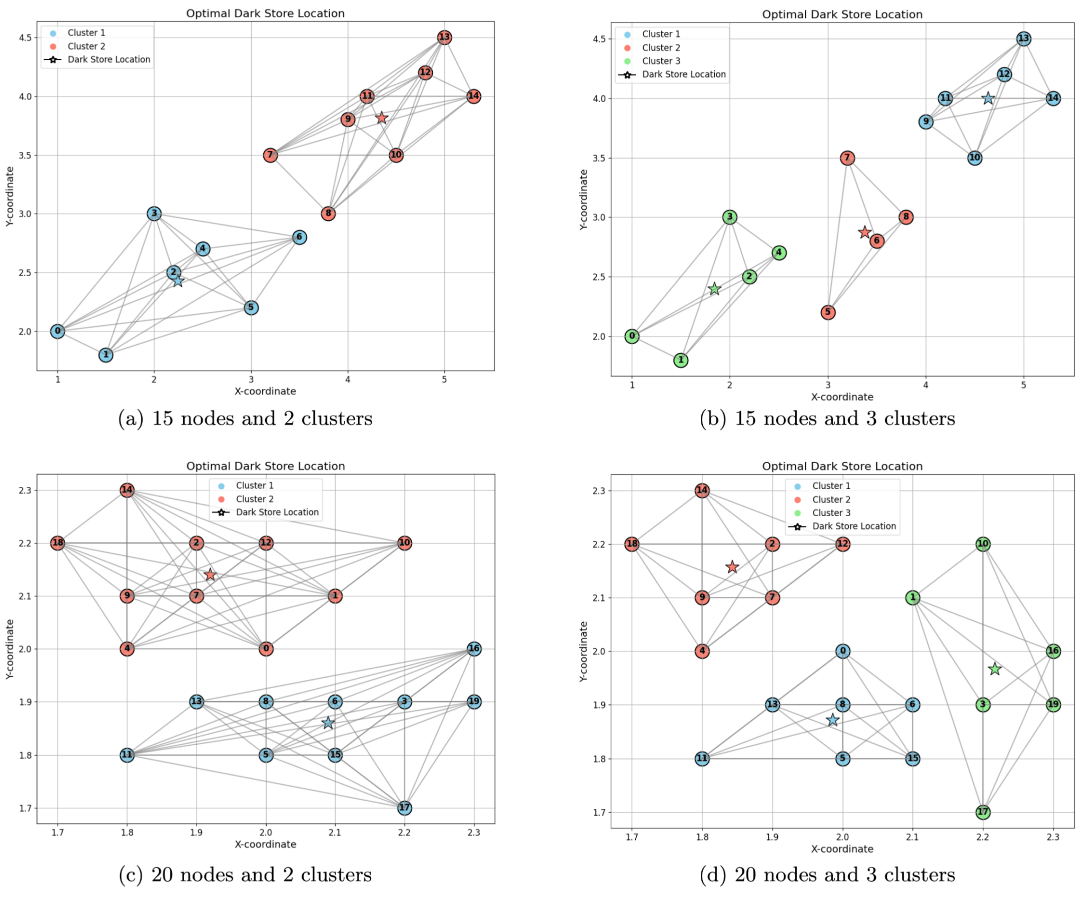
5.6 Urban Mobility and Traffic Management

Optimized dark store locations contribute to better urban mobility and traffic management. By reducing the distance traveled by delivery vehicles, our approach supports sustainable transportation initiatives and alleviates congestion in urban areas.

In summary, the applications of our study extend to various industries and sectors, offering practical solutions for enhancing operational efficiency, reducing costs, and improving the overall customer experience in today's dynamic marketplace.

6. Experimental Results

This section contains the graphs for various cases we ran.



(a) 15 nodes and 2 clusters

(b) 15 nodes and 3 clusters

(c) 20 nodes and 2 clusters

(d) 20 nodes and 3 clusters

Figure 1: Experimental Results with Different Input Sets

7. Discussion

In this study, we investigated the optimal location policy for dark stores in the context of quick commerce companies, aiming to minimize delivery costs and enhance customer satisfaction. Our analysis revealed several key findings that shed light on the strategic placement of dark stores in urban areas.

Our results indicate a clear clustering pattern of demand points. This clustering approach aligns with findings from previous studies on warehouse location optimization.

Interestingly, our study identified a trade-off between operational costs and delivery times. By strategically positioning dark stores within identified clusters, companies can achieve significant reductions in last-mile delivery costs while maintaining service levels.

However, it's important to acknowledge the limitations of our study. The analysis relied on a simplified model of demand patterns and did not account for seasonal variations or dynamic traffic conditions. Future research could incorporate real-time data to enhance the accuracy of location policies.

Moving forward, we recommend exploring dynamic optimization algorithms to adapt dark store locations in response to changing demand patterns. Additionally, integrating machine learning techniques for demand forecasting could further optimize dark store placement strategies.

In conclusion, our study contributes valuable insights into the optimization of dark store locations for quick commerce, emphasizing the importance of data-driven decision-making in supply chain management.

8. Future Work

Potential avenues for future work include:

- Refining the model to incorporate additional constraints or objectives.
- Scaling the approach to handle larger datasets efficiently.
- Exploring alternative optimization algorithms or approaches for solving similar spatial optimization problems.

Overall, this project provided valuable experience in mathematical modeling, optimization, and visualization techniques, which are essential skills in various computational and engineering domains.

9. Conclusion

Our study aimed to optimize dark store locations for quick commerce by employing a combined approach of cluster formation using Mixed Integer Linear Programming (MILP) and centroid calculation.

Key findings and contributions include:

- **Optimal Cluster Formation**: Successful clustering of demand points for efficient resource allocation and operational planning.
- **Efficient Dark Store Placement**: Centroid-based placement of dark stores minimizes delivery distances and operational costs.
- **Operational Efficiency**: Strategic dark store placement reduces delivery times, enhancing overall supply chain efficiency.

Future research could focus on real-world implementation, dynamic optimization, and integration with advanced analytics to further enhance dark store placement strategies in the quick commerce sector. By integrating advanced clustering methodologies with MILP-based modeling, businesses can achieve competitive advantages in the dynamic landscape of rapid delivery services, ultimately improving operational performance and customer experiences.