Modeling Large Scale e-Commerce Distribution Networks

By Nelson Calero, Yao Zhang
Advisor: Milena Janjevic

Topic Areas: Urban Logistics, Last-Mile, Inventory

Summary: As urbanization and e-commerce continue to grow at a rapid rate, companies are rethinking the way they operate their final-mile distribution networks in urban areas. Leading e-commerce players around the world have launched same day or even 30-minute to 2-hour deliveries as a key differentiator to attract online shoppers and to create an unparalleled advantage over competitors. However, how can companies leverage their existing e-commerce distribution networks to fulfill demand across multiple service offerings and how should they jointly consider inventory control decisions in those design decisions? This capstone project developed a framework that companies can use to solve large and complex distribution network problems effectively, and provided managerial insights to best service end consumers with increasingly faster and reliable expectations for deliveries.

Prior to MIT, Nelson Calero worked as an Assistant Manager for Expeditors International of Washington within the Customs Brokerage Product. He received his Bachelor of Science in Industrial Engineering from Lehigh University.

Prior to MIT, Yao Zhang worked as a Senior Manager of Business Transformation for RedMart in Singapore. He received his Master of Science in Industrial and Systems Engineering from Georgia Institute of Technology.

KEY INSIGHTS

1. **Increasing service offerings for time-sensitive deliveries highly impacts the design of the urban last-mile network.**

2. **A company's inventory ordering policy has significant influences on the total network cost and design.**

3. **Clear trade-off exists to determine whether to use local satellite facilities for same-day delivery fulfillment.**

Introduction

As online shopping penetration increases and continues to encroach on traditional offline retailers' territory globally, both e-commerce companies and traditional retailers compete fiercely with each other to gain or retain market share. Online retailers must excel in all dimensions - product range, price competitiveness, cost efficiency, delivery speed, inventory control, etc. - to effectively convert shoppers from traditional retailers and retain their business. Many companies have identified last-mile delivery services as a key differentiator as online shoppers increasingly demand time-sensitive delivery service options.

Unlike traditional retail distribution, e-commerce distribution is characterized by a high number of SKUs and product categories, a large number of smaller shipments, and more and unpredictable geographically-dispersed delivery points. e-Commerce distribution networks are generally composed of "traditional" and "non-traditional" facilities such as central distribution hubs, e-fulfillment centers, transshipment hubs, local transshipment centers, and increasingly, retail and office spaces. All together, they enable the extensive storage and fast distribution of thousands of SKUs within the supply chain network. By offering different delivery service types to end customers, online retailers reduce delivery times and enable immediate product access.

For the global e-commerce parcel delivery market, same-day and instant delivery are expected to reach a combined share of 20% to 25% by 2025, and companies around the world are already adopting multi-tiered distribution networks to serve customers in urban areas. Such recent development has made e-commerce companies very dependent on efficient and flexible supply chain distribution networks that enable large product ranges, high inventory availability, fast deliveries, and low delivery cost.

As a consequence of the heavy reliance on supply chain distribution networks, e-commerce companies need to simultaneously consider an increasing number of decisions such as location planning, inventory control, and transportation. In designing these networks, the network models need to be flexible enough to allow the exploration of as many variables and scenarios as possible, but not to the point that the model becomes too complex and intractable to solve.

Methodology and Data

In this project, our goal is to establish a quantitative model that supports the strategic e-commerce distribution network design by incorporating inventory control decisions into existing location-routing models. The contributions are as follows:

1. Formulation of an integrated mixed integer linear programming (MILP) model that considers location, routing, and inventory decisions
2. Incorporation of inventory control decisions upon multi-echelon location-routing models with continuum approximation
3. Investigation of the impacts and tradeoffs of these decisions on the overall cost of operations and network structure

In the distribution network we consider, there are two levels of facilities and multiple delivery service types as illustrated in Figure 1.

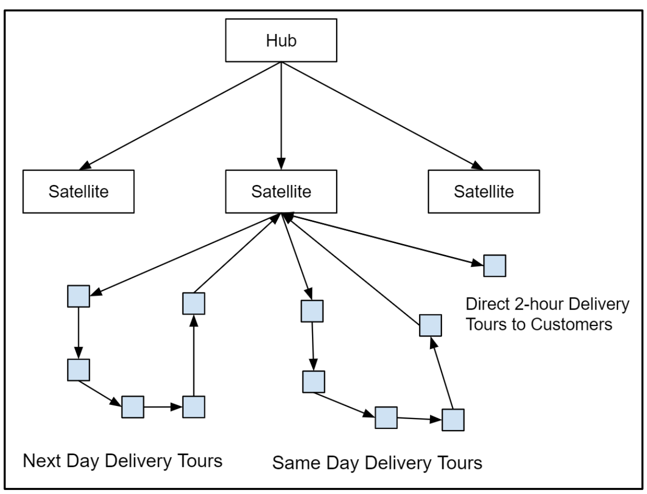


Figure 1: Multi-Tiered Distribution Network

A fixed central distribution hub serves several satellite facilities using one type of first-echelon vehicles to deliver both packed customer orders to satellite facilities for transshipment and unpacked inventory to satellite facilities for storage and order fulfillment. These satellite facilities can function either as a transshipment center (TC), or a distribution center (DC) or both. They serve customers using one type of last-mile delivery vehicles. In addition, three types of delivery services are considered: standard deliveries have a delivery lead time of more than one day, while express deliveries are same-day deliveries. Instant deliveries need to be delivered within 2 hours upon order placement.

We design a mathematical model to support strategic decision making, such as what facilities to be activated for what types of facility service (DC or TC) and which demand segments' delivery service types to be served by which facilities. We define the below sets of decision variables:

- $Y_{j,tc}$= 1, if satellite facility at location *j* is active as a transshipment center; 0, otherwise

- $Y_{j,dc}$= 1, if satellite facility at location *j* is active as a distribution center; 0, otherwise

- $X_{ijs,tc}$= 1, if satellite facility at location j serves delivery service type s in demand segment *i as a transshipment center*; 0, otherwise

- $X_{ijs,dc}$= 1, if satellite facility at location j serves delivery service type s in demand segment *i as a distribution center*; 0, otherwise

The problem is formulated as follows.

min:

K_C^H handling cost at central distribution hub

+ K^F fixed cost of enabling satellite facilities

+ K_S^H handling cost at satellite facilities

+ K^{IH} inventory holding cost at satellite facilities

+ K^{IO} inventory ordering cost at satellite facilities

+ K^T transportation cost from central to satellites

+ K^D routing cost from satellite facilities to demand segments

We apply the model to a synthetic dataset inspired by real-life operations of a Brazilian e-commerce company's last-mile delivery network in metropolitan area of São Paulo, which represents the company's largest and most relevant market. In the synthetic dataset, the company makes about 18,000 customer deliveries a day through a two-echelon network that consists of a large central hub outside of the city and seven satellite facilities in the city.

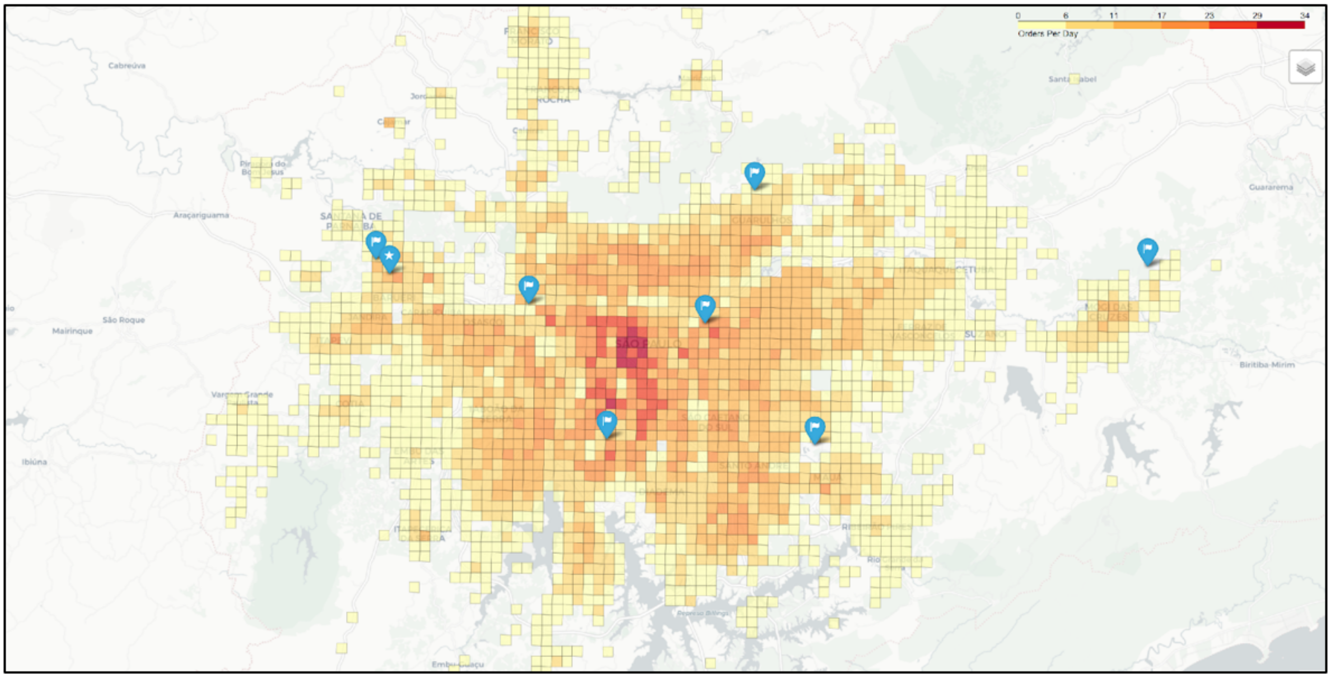


Figure 2: Demand Distribution and Network Design

Three key elements in our model that makes it computationally feasible for large-scale ecommerce networks are described below.

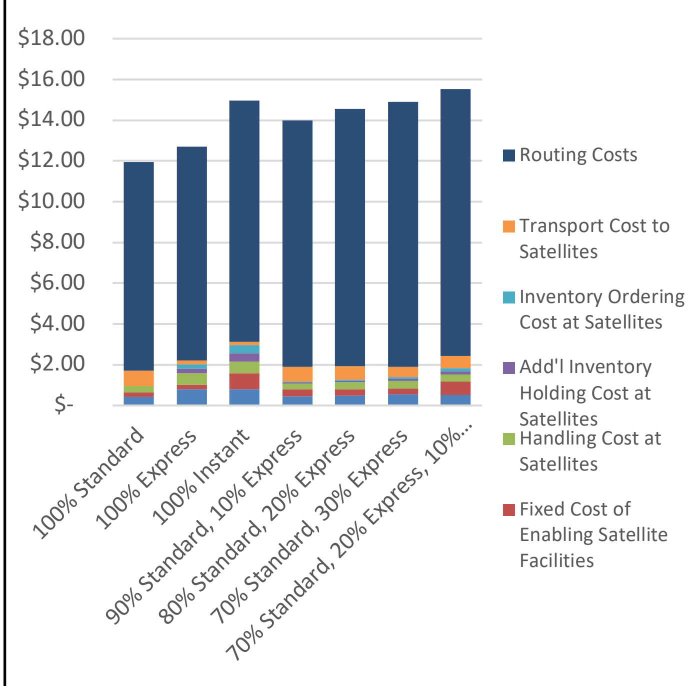
1. 18,000 deliveries per day are divided into 2,400 1 km^2 demand segments as illustrated in Figure 2.
2. Augmented routing cost estimation (ARCE) formula is used to estimate the cost of deliveries between satellite facilities and demand zones.
3. To avoid non-linearity, an iterative approach that declares satellite facilities' inventory policy (days between orders) outside of the model is introduced.

Results and Analysis

We constructed 19 unique scenarios and ran the model on each scenario to examine the effect of different parameters and delivery service types' density on the overall network design and cost. The parameters adjusted for each scenario include:

- **Standard %, Express %, Instant %:** These parameters represent the percentage of total demand that the service level encompasses.
- **Tmax Express**: This parameter represents the maximum allowable service time for express deliveries utilizing transshipment centers.
- **Days Between Orders**: This parameter represents the Days Between Orders to replenish satellite facilities.
- **Satellite Inventory Holding Cost:** This parameter represents the per-item daily inventory holding cost of a demand unit if serviced through a distribution center.

Figure 3: Cost per Parcel Breakdown



For the pure delivery service type scenarios (100% standard, 100% express, or 100% instant deliveries), the cost per parcel increases as we move from standard to instant deliveries as shown in Figure 3. The routing costs are the highest driver of total cost, and the model offsets the higher-tier service levels' increase in routing cost by utilizing distribution centers instead of transshipment centers. This introduces higher fixed and variable handling costs at the satellites but reduces the routing cost increases.

When we examine the mixed delivery service types scenarios, we see that as percentage of demand allocated to express and instant becomes higher, total overall cost turns to be higher. The increase in costs with the added express and instant mainly come from the increased routing costs, fixed facility costs, and the inventory ordering and holding costs.

Four key insights can be derived from the results.

- **Impact of Demand Mix on Network Configuration:** To drive down total system cost, standard deliveries are better suited to be served through transshipment centers while express and instant services benefit from the ability to hold inventory at satellite locations for order fulfillment. The more express and instant deliveries are introduced into the system, the more satellite locations are used for distribution services.

- **Impact of Service Time on Network Configuration:** Using a satellite facility to fulfill same-day deliveries allows for longer last-mile delivery hours due to cutting out the transshipment transit time. When reviewing different allowable service times, we find that the benefits of using satellite locations to fulfill same-day deliveries diminishes only if the transshipment transit time from the central hub to satellite locations is shorter than an hour.

- **Impact of Reordering Frequency on Network Configuration:** The reordering frequency of a distribution center has a significant impact on the total system cost. For the 70% Standard, 20% Express, 10% Instant Mix scenario, the lowest system cost is achieved when inventory is ordered and delivered to satellite locations every 3 days, as illustrated in Figure 4.

- **Impact of Inventory Holding Cost on Network Configuration:** Inventory holding cost will impact the model's decision in how often to replenish inventory to satellite facilities. In addition, as inventory holding costs go up, fewer number of satellite facilities will be deployed for same-day delivery fulfillment but the optimal number and selection of locations vary depending on the cost structure and nearby demand area density.

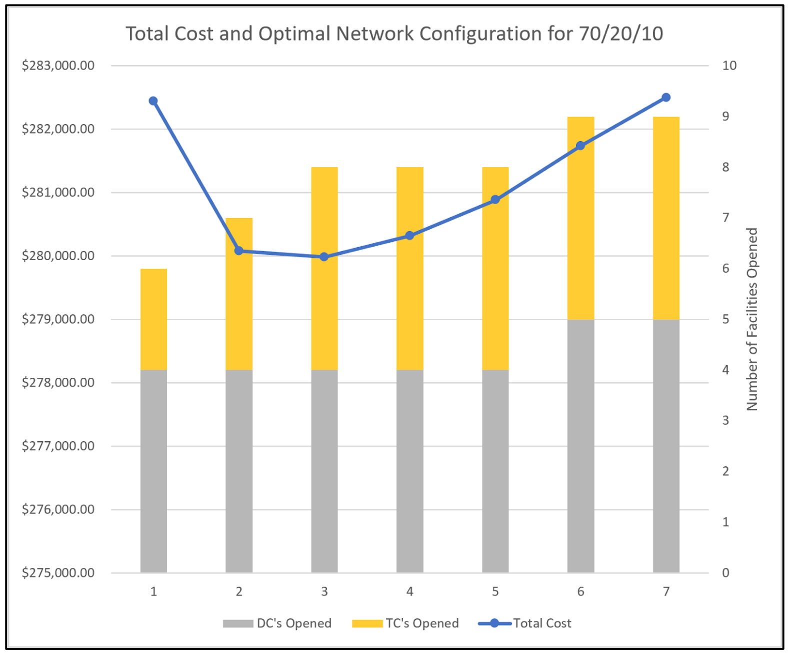


Figure 4: Full Demand Mix Network and Total Cost

Conclusion

To summarize, this project establishes a quantitative model that supports strategic e-commerce distribution network design by incorporating inventory control decisions into existing location-routing models with continuum approximation. By creating this model, we can jointly consider facility location, vehicle routes, and inventory control decisions in a large-scale e-commerce setting.

The results of our model have shown that the overall system costs and network configuration are significantly impacted by the inventory control decisions deployed by an e-commerce retailer. By adopting this framework, e-commerce companies can redesign their last-mile distribution networks to fully leverage their existing assets and gain insights on how to build a robust roadmap for future development.