Sustainable Last-Mile Network Design with Shared Public Microhubs under Competition

Juan C. Pina-Pardo[1], Yann Bouchery[2], Walid Klibi[2]

[1] School of Industrial Engineering, Pontificia Universidad Católica de Valparaíso, Chile
juan.pina@pucv.cl

[2] Center of Excellence for Supply Chain Innovation & Transportation, KEDGE Business School, France
yann.bouchery@kedgebs.com, walid.klibi@kedgebs.com

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1 Introduction

The ever-growing demand for urban last-mile delivery, combined with increasing customer expectations for faster delivery, is placing unprecedented pressure on cities and logistics service providers (LSPs) worldwide. Traditional last-mile distribution systems based on large freight trucks exacerbate traffic congestion and pollution, negatively affecting people's quality of life. Transitioning to more sustainable urban logistics systems is imperative, but ensuring cost-efficiency and profitability for LSPs is far from trivial. Addressing this transition requires a holistic approach that considers the often-conflicting objectives and perspectives of both local authorities and LSPs.

In this work, we address the challenge of designing sustainable urban last-mile logistics networks by integrating the perspectives of multiple stakeholders within a single mathematical framework. To this end, we investigate a hierarchical decision-making problem in which a local authority (e.g., a municipality) aims to repurpose existing, underutilized public spaces into shared microhubs, which can be used by multiple LSPs to transfer their goods from large freight trucks to sustainable vehicles. Potential microhub locations are spread throughout the city and have a given operational capacity, defined as the maximum daily number of parcels that can be sorted and shipped from them. The municipality aims to determine the location of shared microhubs by explicitly anticipating LSPs' reaction and the stochasticity of the demand for the services they offer. The municipality's objective is to maximize the expected demand served via sustainable vehicles across all LSPs, while adhering to budget constraints. These budget constraints could represent, for example, the total public space the city intends to repurpose as microhubs.

To capture uncertain and potentially time-varying demand for services offered by LSPs, we consider a finite operational horizon that begins once microhubs are deployed. Thus, our hierarchical decision-making process considers the following sequence of actions. First, the municipality makes a here-and-now decision (i.e., before any uncertainty realization) determining the locations of public microhubs. Once deployed, in each operational period, uncertainty realization becomes known, after which LSPs compete noncooperatively for using the public microhubs that minimize their total distribution costs while satisfying their customer demand (through their own facilities or via public microhubs). Since public microhubs may be used by multiple LSPs, their operational capacity becomes shared constraints, meaning that LSPs select their own cost-minimizing distribution strategies until a generalized Nash equilibrium is achieved.

We conducted a comprehensive review of the academic literature and found that, while creating sustainable last-mile logistics systems requires a holistic approach that accounts for the interests of both local authorities and LSPs, most literature examines problems from the perspective of a single stakeholder [1]. Among the few works that address hierarchical decision-making or settings involving multiple decision-makers, none have considered uncertainty, a characteristic inherent to last-mile delivery. Moreover, even when expanding the scope to other supply chain and logistics problems, research on hierarchical decision-making processes under uncertainty remains limited [2]. Therefore, our work is among the first to bring together, within a single mathematical framework, the sustainability-oriented goals of local authorities and the economically driven objectives of LSPs when designing city logistics systems under uncertainty and competition.

2 Modeling and Solution Approach

We conceptualize the problem as a stochastic single-leader, multi-follower Stackelberg game and propose a two-stage stochastic bilevel programming formulation, where the first stage captures the municipality's decisions, while the second stage models the generalized Nash equilibrium problem faced by LSPs in each demand realization. We derive several structural properties to prove the existence of equilibria and characterize optimal lower-level problem solutions. Based on these structural properties, we propose an efficient branch-and-Benders-cut approach that does not rely on classical single-level reformulations (e.g., based on Karush-Kuhn-Tucker conditions), which turns out to be computationally intractable. We also introduce algorithmic enhancements to accelerate our branch-and-Benders-cut approach, including a warm-start strategy and an upper-bounding procedure.

3 Numerical Experiments and findings

We build a comprehensive case study inspired by the pilot program recently announced by the New York City Department of Transportation, which aims to designate off-street and curbside locations as microhubs for authorized LSPs [3]. Based on this pilot program, we create realistic problem instances involving four major LSPs serving about 500,000 customers daily in Manhattan. Our results show the effectiveness of our branch-and-Benders-cut approach to efficiently find optimal solutions. We also report the value of the stochastic bilevel solution and derive several managerial insights into the design of sustainable urban distribution networks with shared microhubs under competition. Our findings show optimal solutions balance depot connectivity and customer proximity. Besides, taking the inherent competition between LSPs into account at the design stage allows municipalities to make much better use of their public space. This leads to great improvements in the share of sustainable deliveries even with limited public space available.

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