Georgia Tech Physical Internet Center
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Generating space clusters for urban logistics in hyperconnected networks

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Outline

Problem definition

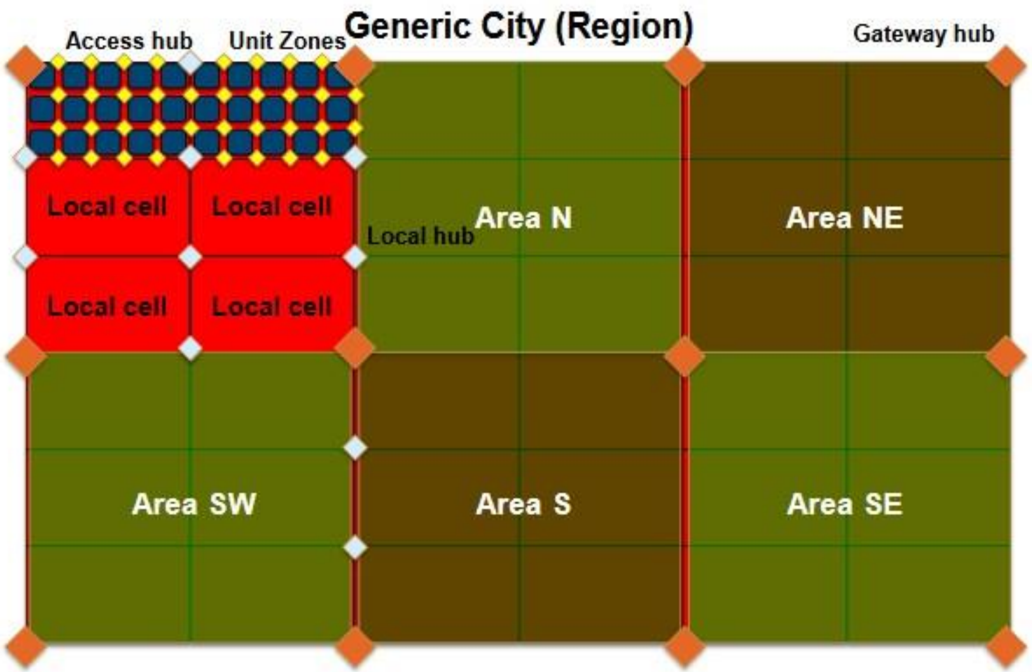
Problem definition

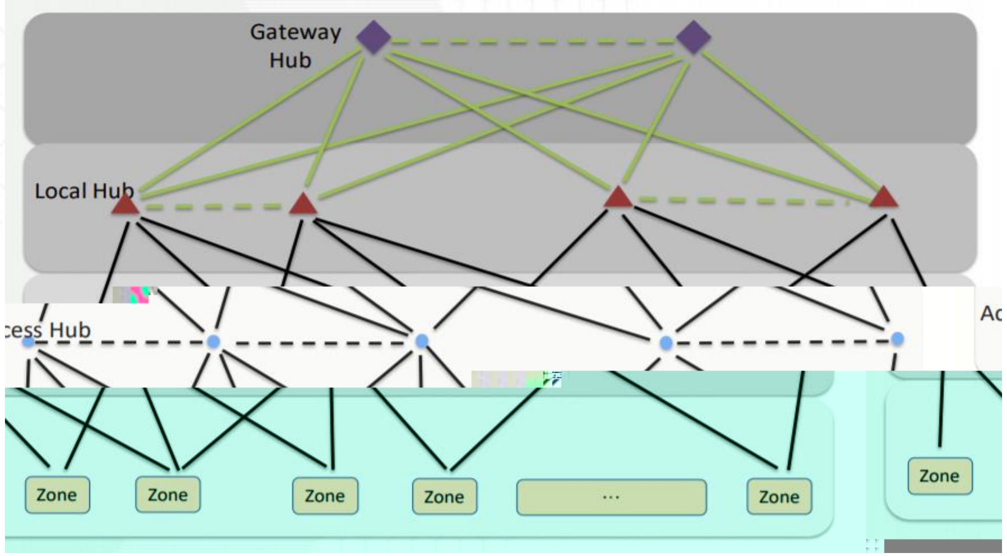
Space clusters in hyperconnected logistics

Given a set of small atoms (unit zones), cluster them into larger local cells, and cluster the local cells into urban areas

Clusters are incident to hubs and define feasible zone-to-hub and hub-to-hub flows

The space clustering structure is critical to multi-tier web operations, and may evolve over time





Source: Montreuil B., S. Buckley, L. Faugere, R. Khir & S. Derhami (2018). Urban Parcel Logistics Hub and Network Design: The Impact of Modularity and Hyperconnectivity, **Progress in Material Handling Research: 2018**, Ed. A. Carrano et al., MHI, Charlotte, NC, U.S.A. https://digitalcommons.georgiasouthern.edu/pmhr_2018/19/

Goal

Find a good solution to the space clustering problem

A good space cluster design can be used
to structure an efficient, resilient, sustainable network

Each cluster should be

- **Contiguous**
- **Compact** geographically
- **Balanced** (roughly equal demand in terms of logistic work)
- **Resilient**

Modeling and input

Represent map of unit zones as graph

- vertex set is the set of UZ
- edges represent pairs of adjacent UZ

List local and gateway hubs

- capacity thresholds
- optional additional modules with capacities and prices
- neighborhood of unit zones within adequate distance to be served by

Estimate operating costs

- for each pair of unit zones
- for each pair of unit zone , hub

Estimate demand

- single number for each pair of unit zones

Methodology

MIP decision variables and objective

Assignment variables

, : UZ in local cell , urban area

, : UZ and both in local cell , urban area

Flow variables

, vertical flow between and through local or gateway hub

, : horizontal flow between and

$$OBJ = \sum_{i,j,h} (\lambda_{ih} + \lambda_{jh}) d_{ijh}^{LH}$$

Cost of vertical flow through local hubs

$$+ \sum_{i,j,h} (\lambda_{ih} + \lambda_{jh}) d_{ijh}^{GH}$$

Cost of vertical flow through gateway hubs

$$+ \sum_{i,j} (\gamma^C f_{ij}^C + \gamma^A f_{ij}^A)$$

Cost of horizontal flow

$$+ \delta \sum_{i,j,k} \lambda_{ij} e_{ijk}^C$$

Compactness measure

$$+ \sum_{l,h} \beta_l \, b_{lh}$$

Penalties for exceeding hub capacity (balance and resiliency)

$$+ \sum_{h,m} \pi_{hm} z_{hm}$$

Cost of adding modules to hubs

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MIP constraints: overview

Assignment: each UZ is in a unique local cell and urban area

- Local cells are properly clustered into urban areas
- Unit zone in local cell can send flow through hub if and only if intersects

Flow: all demand is met

- Flow between and can be vertical, or horizontal if and in same cluster

Resiliency: for each pair and at most parameter , proportion of the flow passes each local/gateway hub

Contiguity: each cluster is a connected region

- Implemented using the rooted tree flow constraints introduced by Shirabe, 2009

Capacity:

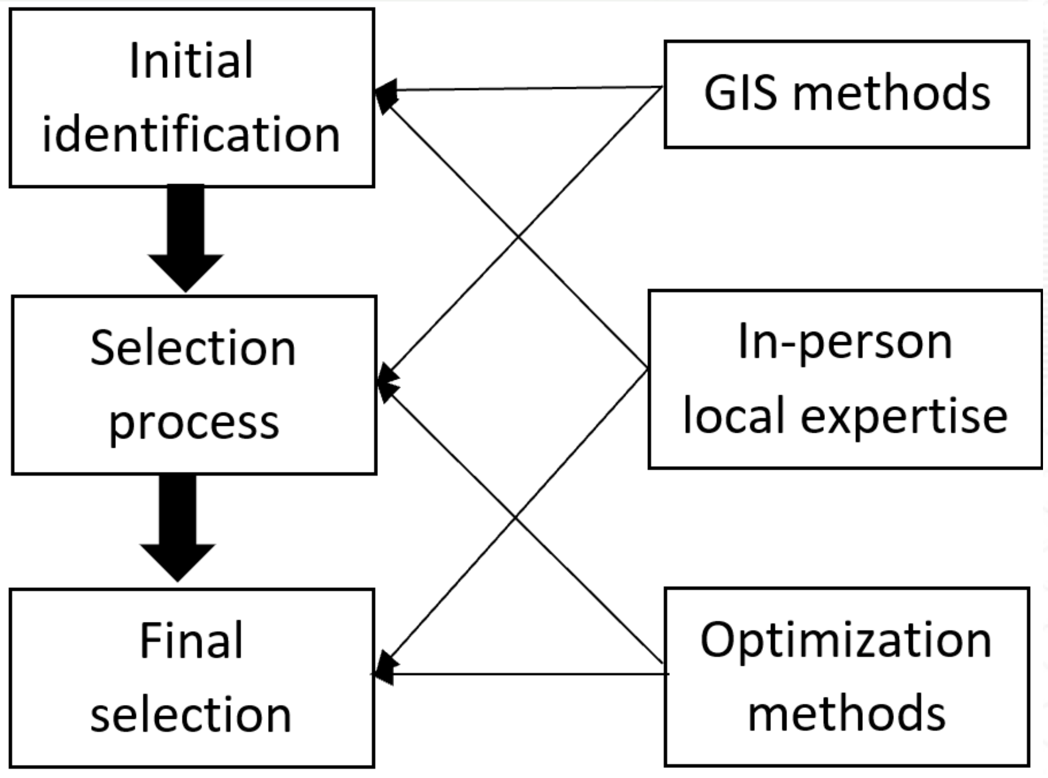
- Depending on local constraints, additional modules may be added at specified cost to increase capacity

Source: Shirabe, T. (2009): Districting modeling with exact contiguity constraints. Environment and Planning B: Planning and Design, 36(6):1053 1066.

Integration with network design

Hub candidate selection

Input: very large set of points in the city
Output: smaller set of candidates for access and local hubs



Network design

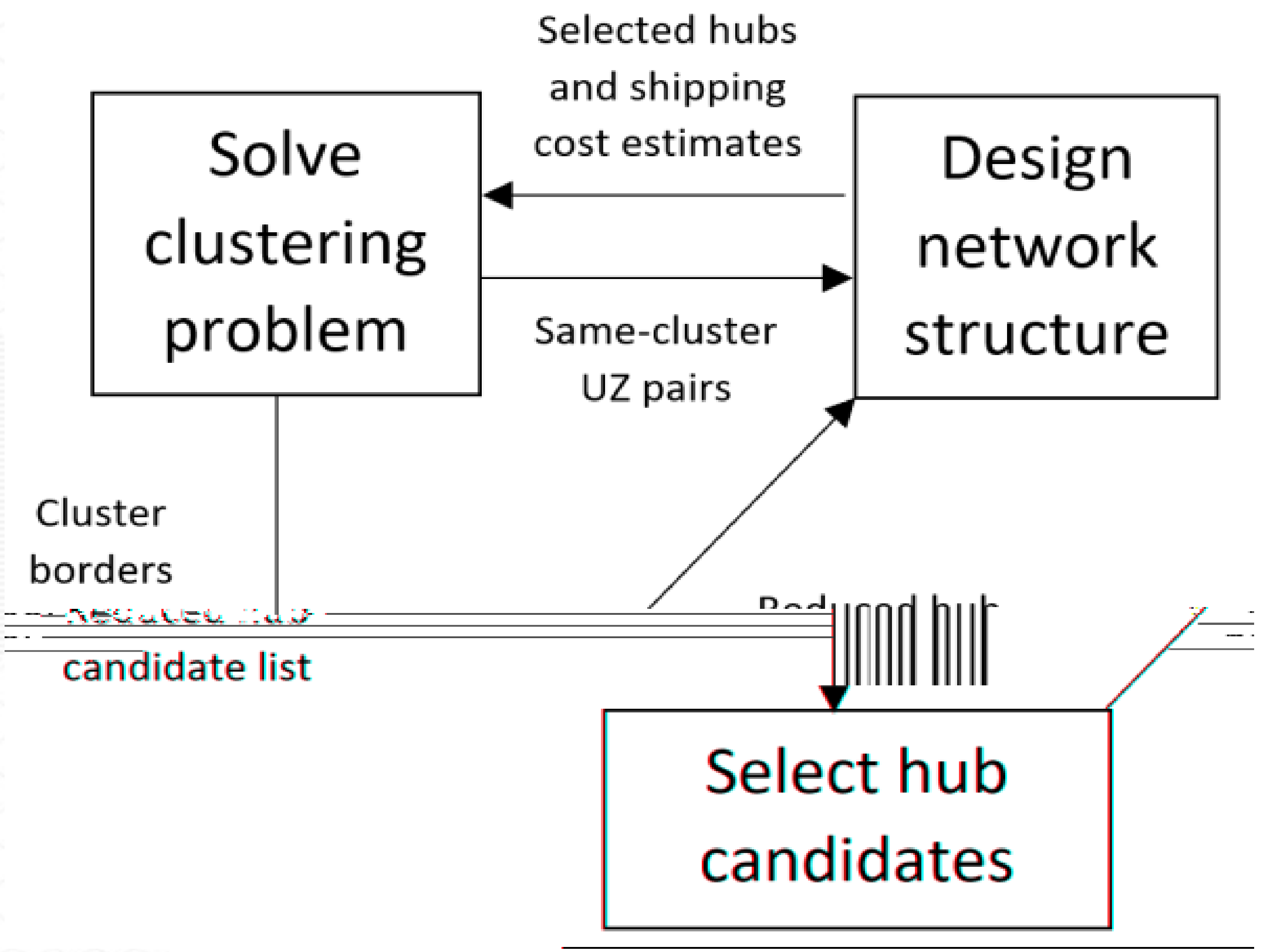
Input
- demand profile
- hub candidates
- feasible arcs (from clustering)
- local constraints

Output
- set of opened hubs and arcs
- feasible flow pattern

High-level iterative design

Space clustering complements and integrates with hub candidate selection and network design problems

High level method:
Solve each optimization problem in turn, using its output as input to the next problem



Striping

Warm-starts from striping

The dynamic striping algorithm of Hettle et al. (2021) for graph partitioning can generate clusterings to use as warm starts for the MIP

Input:

- Graph with vertex weights for all
- Desired number of clusters
- Balance parameter (all clusters have total demand within fraction of average)
- Hamiltonian path on
  - Obtained using uncrossing approximation algorithm for the traveling salesman problem

Output:

- Balanced, compact, contiguous clustering on

- Clustering is used to set flow values in warm-start
- Runs in time, so can be quickly repeated with different path/parameters to obtain multiple initial configurations

Source: Hettle C., S. Zhu, S. Gupta, Y. Xie (2021): Balanced Districting on Grid Graphs with Provable Compactness and Contiguity, https://arxiv.org/abs/2102.05028 (preprint)

Experimental results

Experiment design

We test the model on part of the SF Express network in Shenzhen

The Hamiltonian path, starting at the northwest (light) and ending at the east (dark)

Input and warm start

Clustering

Set of local cells in the southwest of Shenzhen, created using the striping method

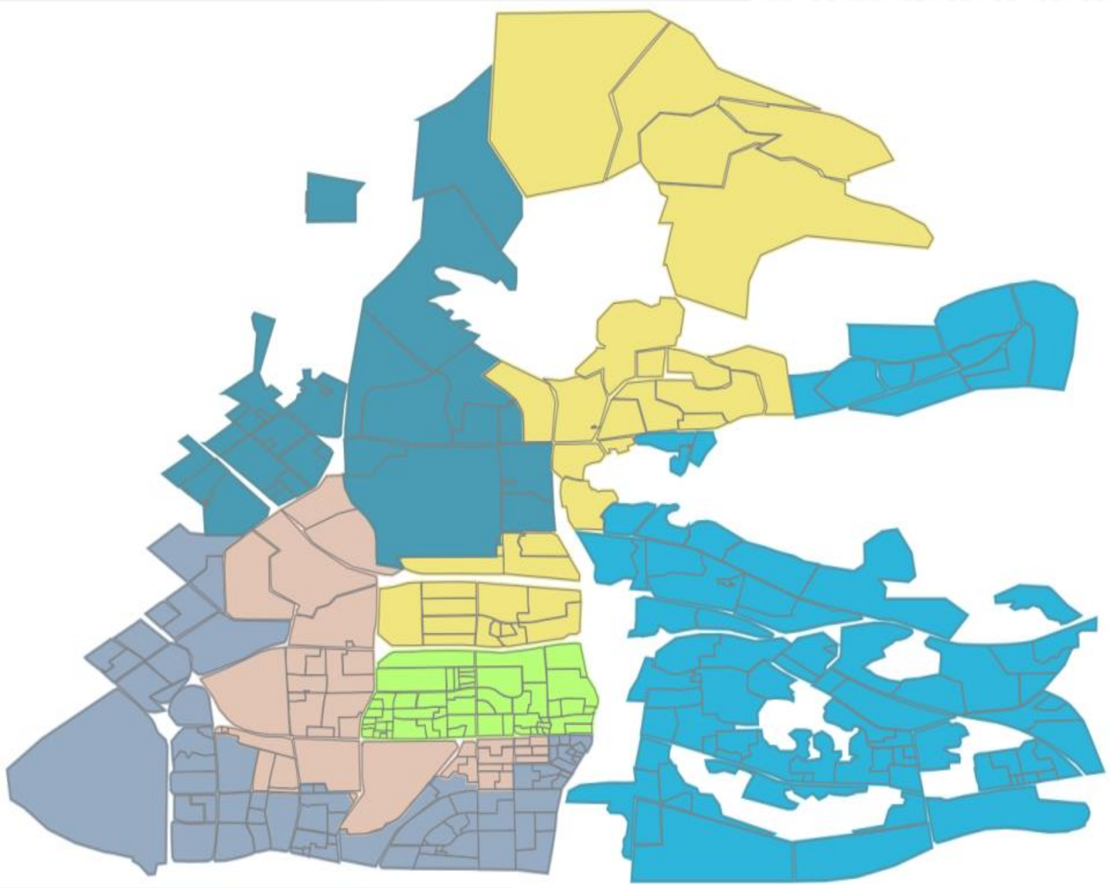
Demand profile

Based on customer behavior and SF Express market share

Over 80% of demand associated is intercity, going to or from a gateway hub

Hub locations and capacities

Experiment results



	Flow cost	Compactnes ss	Balance	Modules s	Total cost
Warm-start clustering	4.54 10^{8}	8.32 10^{7}	2 10^{7}	2 10^{7}	5.77 10^{8}
New clustering	4.32 10^{8}	7.62 10^{7}	2 10^{7}	1.5 10^{7}	5.43 10^{8}

Conclusion and Future Steps

The space clustering problem in hyperconnected logistic networks can be efficiently solved using a MIP

Geographic compactness and contiguity, hub demand capacity, and resiliency are all effectively considered

Clustering effectively combines with and improves the tractability of methods for hub selection and network design

Increased use of additional heuristics may further improve performance, particularly in large instances

In-depth optimization experiments iterating between space clustering and network design under alternative robust service time targets

Simulation-based experimentations under stochastic scenarios with alternative integrated space clustering, network design and operations solutions