# Optimizing on-demand feeder service areas via greedy spatial expansion: comparison with simple geometries

Hanna Vasiutina*[1], Olha Shulika[1,2], and Rafal Kucharski[1]

[1]Faculty of Mathematics and Computer Science, Jagiellonian University, Krakow, Poland
[2]Faculty of Tourism and International Communications, Uzhhorod National University, Uzhhorod, Ukraine

## Short summary

Service areas in demand-responsive feeder systems are often defined using simple geometric shapes or existing administrative boundaries, without considering how their geometry affects system performance. This paper approaches service area design as a spatial decision problem and examines how different geometric assumptions influence operational outcomes. We propose a simulation-based optimization framework in which the service area is constructed iteratively by expanding the region based on its contribution to system performance. This allows us to compare the optimized configuration with commonly used ad-hoc geometries, including circular, rectangular, and administrative areas.

The framework is demonstrated in a case study of a feeder service in the Skotniki district of Kraków, Poland. The results show that the optimization-driven configuration outperforms the baseline geometries in key performance indicators. This indicates that simple geometric shapes may lead to less efficient designs, and that service area geometry should be treated as a decision variable in the planning of demand-responsive feeder systems, rather than as a fixed construct.

**Keywords**: on-demand feeder services; service area design; simulation-based analysis; spatial optimization.

## 1 Introduction

Demand-responsive feeder services are increasingly used to connect low-density areas with high-capacity public transport (Vansteenwegen et al., 2022; Itani et al., 2024). Their flexibility allows them to respond to spatially distributed demand, which is difficult to serve efficiently with fixed routes. However, this flexibility also complicates system design, as performance depends on how demand patterns, routing logic, and operational parameters interact.

A key design element in this context is the service area, which determines which users can access the system and how far vehicles are expected to operate. While a smaller area may limit demand and reduce system viability, a larger one can capture more ridership and encourage a shift from private cars, at the same time increasing travel times and creating competition with active transport modes (Kaddoura et al., 2020).

In practice, service areas are often defined using simple geometries, such as distance-based buffers around a hub, or by following administrative borders (Nahmias-Biran et al., 2021). These choices are usually motivated by simplicity or policy constraints rather than system performance. More advanced approaches use simulations to evaluate alternative configurations, accounting for demand patterns and operational dynamics (Fielbaum & Alonso-Mora, 2024; Vasiutina et al., 2025).

Despite these developments, the geometry of the service area itself is rarely examined. Whether a it is circular, rectangular, or irregular, it is typically not treated as a decision variable, and its effect on system is often overlooked.

This paper addresses this gap from two perspectives. First, we introduce a simulation-based approach for constructing feeder service areas using a greedy spatial expansion procedure, in which the service region is built incrementally based on its contribution to system performance. Second, we compare the resulting configuration with commonly used ad-hoc geometries, including circular and rectangular areas, as well as the existing administrative boundary. All configurations are evaluated using the SimFLEX simulation framework, which models travel demand, mode choice, and ride-pooling operations (Vasiutina et al., 2025). This enables a consistent comparison based on key performance indicators (KPIs).

## 2 Methodology

We consider the task of defining a service area for a feeder system as a greedy iterative expansion heuristic in which system performance depends on the extent and structure of the region served. Rather than defining a fixed geometry, the goal is to identify a service region that offers favorable outcomes when evaluated through simulation.

To explore possible configurations, the service area is built progressively starting from the transit hub. At each stage, the current region is modified by incorporating adjacent spatial units, allowing the construction process to follow a sequence of incremental changes.

Candidate service areas are represented as sets of H3 hexagonal cells (Uber, 2026). Each configuration is assessed using SimFLEX framework, which produces various KPIs, such as added value $\Delta V$, feeder attractiveness $\Delta A$, increase in passenger-hours $\Delta T_p$, decrease in vehicle-hours $\Delta T_v$, average occupancy $O$, and fleet size change $\Delta F$). The sequential expansion of the service area therefore reflects a search process guided by simulated system performance rather than by predefined geometric rules.

The expansion procedure follows a greedy search strategy in which candidate regions are evaluated and extended iteratively. Let $S_t$ denote the service area at iteration $t$, initialized as the spatial unit containing the transit hub. At each iteration, the algorithm proceeds as follows:

1. Candidate generation. Identify all neighbors of the current service area and construct candidate shapes by adding one neighboring hexagon at a time:

$$C_t = \{S_t \cup \{h\} \mid h \in N(S_t)\}, \tag{1}$$

   where $N(S_t)$ denotes the set of spatial units (hexagons) adjacent to the boundary of $S_t$.

2. Simulation-based evaluation. Each candidate configuration $c \in C_t$ is evaluated using a set of KPIs obtained by simulations $\{k_{c,1}, k_{c,2}, \ldots, k_{c,M}\}$.

3. Score calculation. The KPIs are normalized for each candidate shape and aggregated into a composite score:

$$Q(c) = \sum_{m=1}^{M} w_m \cdot \tilde{k}_{c,m}, \tag{2}$$

   where the normalized KPI values are defined as:

$$\tilde{k}_{c,m} = \frac{k_{c,m} - k_m^{\min}}{k_m^{\max} - k_m^{\min}}, \tag{3}$$

   with $k_m^{\min} = \min_{c \in C_t} k_{c,m}$ and $k_m^{\max} = \max_{c \in C_t} k_{c,m}$. The weights $w_m$ reflect the relative importance of each indicator.

4. Selection of a new shape. The next configuration is selected as the candidate with the highest score:

$$S_{t+1} = \arg\max_{c \in C_t} Q(c). \tag{4}$$

5. Stopping condition. The procedure is repeated until no further improvement is observed as

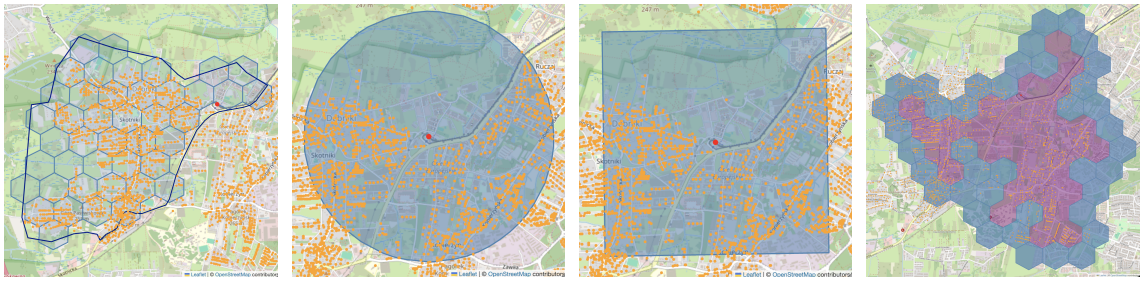
$$\Delta Q_t = Q(S_t) - Q(S_{t-1}) \leq \varepsilon, \tag{5}$$

   where $\varepsilon$ defines the minimum improvement that is considered significant. The algorithm terminates when such improvements are not observed for a predefined number of consecutive iterations, or when a maximum service area size is reached.

To account for the stochastic nature of simulation outputs and demand variability, the expansion procedure is repeated across multiple independent demand realizations. This results in a set of optimized service area shapes. The final service area is then determined using a spatial frequency analysis, in which the probability of each hexagon being included in the optimal configuration is estimated. This approach ensures that the resulting service area represents the spatial units that most consistently contribute to system performance under varying demand conditions.

## 3 Results and discussion

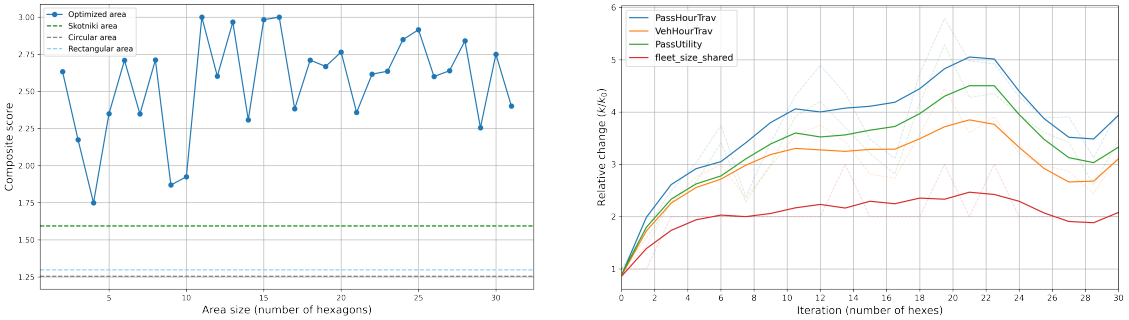
We apply the proposed framework to a case study in Kraków, Poland, focusing on the Skotniki district and the Czerwone Maki transit hub, where on-demand feeder buses are currently operating. We compare the performance of three baseline geometries against the optimization-driven alternative obtained through the proposed greedy expansion algorithm (Fig. 1).
The baselines include: (a) the existing administrative service area Skotniki, (b) a circular region representing uniform distance-based coverage, and (c) an axis-aligned rectangular region, both centered at the hub. The dimensions of these shapes are calculated such that their total surface area ($m^2$) is equal to that of the Skotniki service area. The optimized shape is determined dynamically: starting from the hub, the service area expands hexagon-by-hexagon until it reaches either a predefined maximum of cells (corresponding to the size of the Skotniki area) or a stopping condition (Eq. 5) is met. For this case study, we select SimFLEX-obtained KPIs that capture the trade-offs between passenger benefits and operational performance: added value $\Delta V$, average occupancy $O$, and fleet size change $\Delta F$. These indicators are normalized and aggregated into a composite performance score $Q$ (Eq. 2), where the weights $w_m$ reflect their relative importance.



(a) Skotniki area (b) Circular area (c) Rectangular area (d) Optimized area

Figure 1: Spatial comparison of service areas: (a) existing administrative region Skotniki, (b) circular, (c) rectangular, and (d) optimized shape obtained via greedy spatial expansion.

The evolution of system performance during the service area expansion is illustrated in Figure 2. The composite score (Fig. 2a) shows that the optimization-driven shape consistently outperforms the baseline geometries for most area sizes. The largest improvements occur in early iterations, while later expansions bring smaller marginal gains. The absolute KPIs trajectory (Fig. 2b) indicates that, as the service area expands, both passenger-related and operational measures increase, reflecting improved demand coverage and service quality. However, the rate of improvement decreases over iterations, indicating diminishing benefits from further expansion.




(a) Composite score (b) Absolute KPIs

Figure 2: Performance evolution of the composite score (a) and absolute KPIs (b) as the service area expands.

Compared to baseline geometries, the optimized service area is more spatially selective. While circular and rectangular configurations include low-demand and operationally inefficient regions, the optimized configuration expands unevenly around the hub, prioritizing areas that contribute positively to system performance.

## 4 Conclusions

This paper investigates the role of service area configuration in the design of on-demand feeder systems and proposes a simulation-based greedy spatial expansion approach to construct service areas iteratively based on their contribution to system performance.
We demonstrate the proposed method in a case study in Kraków, where the optimized configuration is compared with commonly used baseline geometries, including circular, rectangular, and administrative areas. The results show that the optimization-driven approach achieves higher performance in terms of the selected indicators and the composite score.
The findings highlight that service area geometry is a critical design variable rather than a neutral constraint: it directly impacts system performance, affecting both demand coverage and operational efficiency. Although simple geometric shapes offer practical approximation, they may include areas that do not contribute positively to system outcomes.
A main limitation of the proposed approach is its computational complexity, as the greedy expansion relies on simulations of multiple candidate configurations at each iteration - a process that scales significantly as the service area grows. Future work will investigate more efficient optimization strategies, while also incorporating an equal-demand setup, additional performance indicators, and more diverse demand scenarios. Furthermore, considering temporal variations in demand and multi-hub configurations would further enhance the applicability of the proposed approach.

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