SEAMLESS SHARED URBAN MOBILITY

# Schedule Integration Tool

Project deliverable D2.3

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# Project Executive Summary

The objective of the SUM project is to transform current mobility networks towards innovative and novel shared mobility systems (NSM) integrated with public transport (PT) in more than 15 European Cities by 2026, reaching 30 by 2030. Intermodality, interconnectivity, sustainability, safety, and resilience are at the core of this innovation. The outcomes of the project offer affordable and reliable solutions considering the needs of all stakeholders such as end users, private companies, public urban authorities.

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# Deliverable executive summary

## 1.1 Key words

Multimodality, modal integration, scheduling optimisation, transfer optimisation, trip planning

## 1.2 Summary

The Deliverable 2.3 is a Demonstrator. It consists of (a) the present document, that explains the tools developed for the integration of new shared modes (NSM) and public transport (PT), the document includes technical explanations, and (b) the codes for all the tools developed, which is made available open-access in scientific repositories, with all relevant links included in the present document.

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# 1 List of abbreviations and acronyms

| Acronym | Meaning |
|---|---|
| **ALNS** | Adaptive Large Neighbourhood Search |
| **ASV** | Autonomous Surface Vessel |
| **BRP** | Bike Rebalancing Problem |
| **BS** | Bike-sharing |
| **C** | Clustered |
| **GTFS** | General Transit Feed Specification |
| **KPI** | Key Performance Indicator |
| **LL** | Living Labs |
| **MARL** | Multi-Agent Reinforcement Learning |
| **MILP** | Mixed-Integer Linear Programming |
| **MSA** | Method of Successive Averages |
| **NSM** | New Shared Modes |
| **OD** | Origin-Destination |
| **OTP** | OpenTripPlanner |
| **PT** | Public Transport |
| **R** | Random |
| **RAPTOR** | Round-Based Public Transit Routing |
| **RC** | Random-Clustered |
| **SimFLEX** | Simulation Framework for Feeder Location Evaluation |
| **SM** | Shared Modes |
| **SUM** | Seamless Shared Urban Mobility |
| **TRL** | Technology Readiness Level |
| **WP** | Work Package |

# 2 Purpose of the deliverable

## 2.1 Attainment of the objectives and explanation of deviations

The objectives related to this deliverable have been achieved as scheduled.

Related to task 2.3, this deliverable is the implementation of a series of interrelated tools supporting mobility service providers in designing and assessing service coordination measures. So far, many Living Labs are already using or going to use these tools (please refer to section 3 of the present document for more details). The codes of the apps composing these tools are added as a link to the online Open Data Platform. The Schedule Integration Tool will be enhanced from TRL 4 to TRL 7 by the end of the project, and a process has been set to make sure they will reach the target TRL by Month 36.

## 2.2 Intended audience

The results of this deliverable are intended for the project partners, the Living Labs, Observer cities, external researchers and practitioners interested in new methodologies to analyse and optimise the integration of new shared modes and public transport. This deliverable will be made available to the wider public (PU dissemination level).

## 2.3 Structure of the deliverable and links with other work packages/deliverables

The Deliverable 2.3 is a Demonstrator. It consists of the present document, which explains the tools developed for the integration of new shared modes (NSM) and public transport (PT), and the codes for all the tools developed, which are made available open-access in scientific repositories (hyperlinks to them are included in the present document). All open-access tools developed as part of Task 2.3 are also made available on the SUM Open Data Platform.

In the next sections the models are described. Section 3.1 describes our multimodal trip planner, which is in its current test application phase in the city of Rotterdam. Section 3.2 shows our Fleet optimization tool for the combined design of bike-sharing and public transport (PT). Section 3.3 is about fleet rebalancing for new shared modes (NSM), Section 3.4 is about rescheduling public transport operations integrated with shared mobility, and Section 3.5 is about ride-pooling and its combined design with fixed-route public transport. The current level of application in our Living Labs is mentioned throughout Section 3. Finally, Section 4 discusses the main conclusions of Task 2.3.

This deliverable is part of the work of WP2 which aims to analyse the integrated planning and operations of new shared modes and public transport. The objective is to improve the seamlessness of multi-modal travellers' experience by developing, applying and deploying techniques and tools for integrating public transport, shared on-demand and micro-mobility services. It relates to Tasks 2.1 (Shared fleet availability predictions for multi-modal trips integration in Mobility as a Service) and 2.2 (Shared on-demand fleet management). It is also linked to WP4 which gathers the applied work in all Living Labs, because the tools developed in Task 2.3 will continue to be applied to the Living Labs in Year 3 of the SUM project.

# 3 Tools for the seamless integration of new shared modes and public transport

Multimodal trip planning and schedule coordination has the potential to use the strengths of multiple transport modes in a synergistic way. We develop complementary frameworks that find optimal trip planning advice to users and optimal fleet sizes for new shared modes (e.g., shared bikes) to be used in combination with public transport, taking into account the service quality provided to users and the revenues and costs of NSM and PT operators.

## 3.1 Multimodal trip planner

Our first mobility scenario assumes supply as given, i.e., fixed total fleet size and trip fares. In this scenario, the trip planner assigns users to modes and routes according to their preferences, in a way to maximise the total user benefit across the population. This is an extension of the commonly available trip planners that do not take user preferences into account.

WP2 partners propose a preference-based optimization tool for multimodal trip planning. This tool, developed by TU Delft, integrates public transport, ride-pooling services, and shared micro-mobility options (e.g., e-scooters and bikes), offering travellers flexible, low-emission alternatives that align with their individual preferences. At the core of the system is a mixed-integer programming model that embeds user preferences directly into the objective function, ensuring that the recommended travel plans are not only efficient but also personally suitable. To handle real-time and dynamic mobility demands, we develop a meta-heuristic framework that combines a customized Adaptive Large Neighbourhood Search (ALNS) algorithm with other tailored optimization techniques. A rolling horizon approach enables the system to adapt dynamically to incoming requests and changing availability. Partners validated the selected approach using real-world data from a suburban area of Rotterdam, the Netherlands. The results show that the developed algorithm efficiently generates near-optimal multimodal travel plans, balancing user preferences with system constraints. This study now is under review in the academic journal "*Transportation Research Part E: Logistics and Transportation Review".*

Regarding users, preferences are incorporated into the objective function of the optimization model, through different taste parameters in modal utilities for the following segments of passengers: A. aggregated population; B. commuters and non-commuters; C. passengers who are familiar or unfamiliar with NSM; D. passengers who use PT less or more than once per week, E. passengers with low or high incomes; F. female or male passengers; G. passengers with different education levels; H. passengers who have or have not used SM; I. passengers with different ages. The maximum expected utility reached by the travelling population is the users' benefit, which depends on the combination of modes available and use, and on the quality of service provided by each travel alternative (e.g., access, waiting and in-vehicle times, price per trip, comfort and modal reliability), which in turns depends on the level of supply being offered (frequency and density of lines in public transport, number of stations and availability of shared bikes, etc.).

Figure 1 illustrates the multimodal trip planning tool that accounts for heterogeneous passenger preferences to generate personalized and sustainable transport plans. The tool works through a journey planning module, where diverse passengers (e.g., elderly, students, cyclists) submit travel requests to a multimodal transport platform. The platform uses utility functions to model passenger preferences and integrates them into an optimization model. This model identifies and evaluates multiple transport alternatives –comprising different modes and routes – for each passenger, assigning utility scores to reflect their suitability. By optimizing over these alternatives, the tool produces a coordinated transport plan that balances efficiency and individual satisfaction across the entire passenger population.

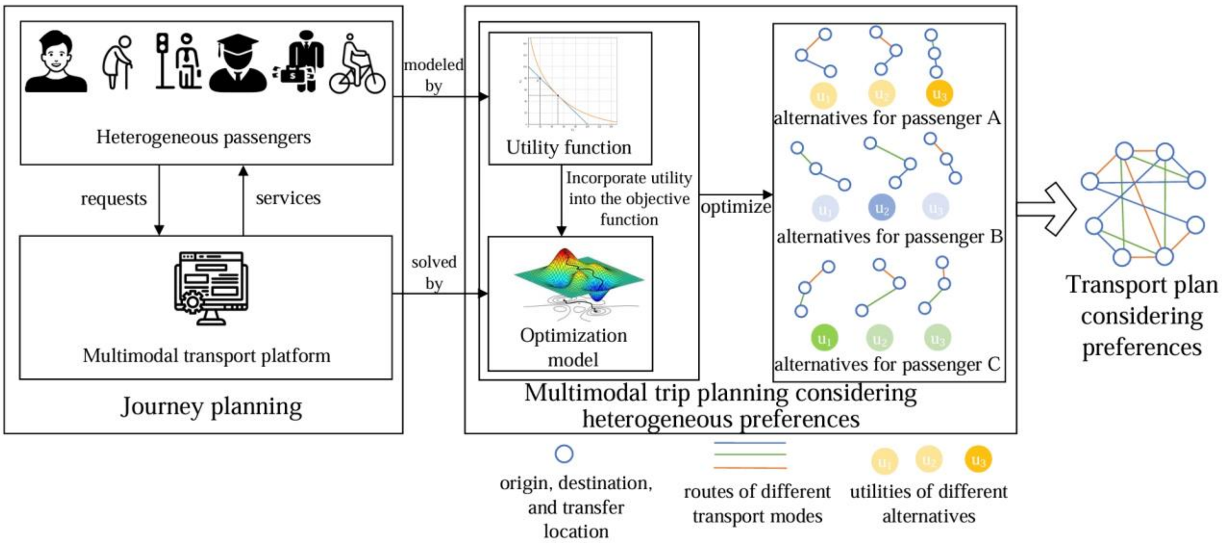
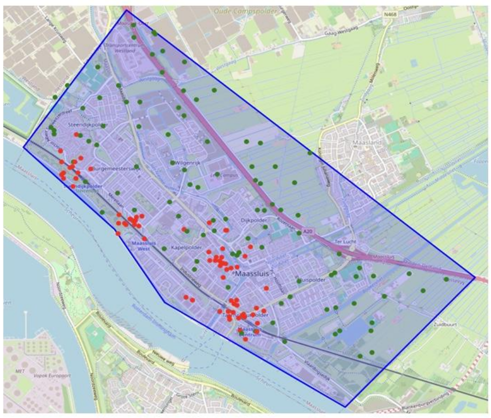
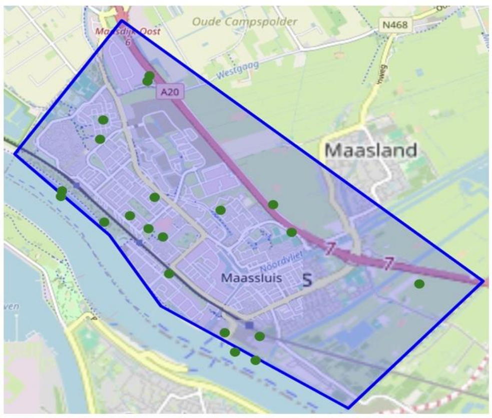



Figure 1. Multimodal trip planning tool

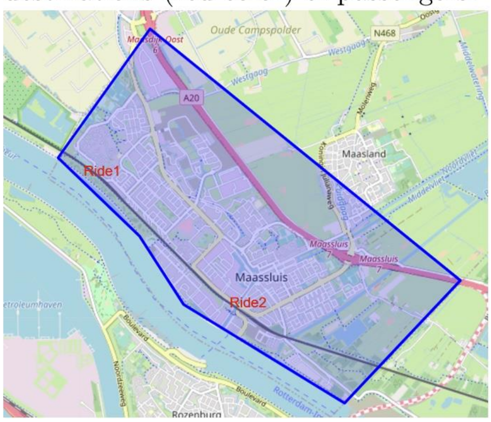
Figure 2, below, shows requests and vehicles in the area partners have conducted experiments in the city of Rotterdam.



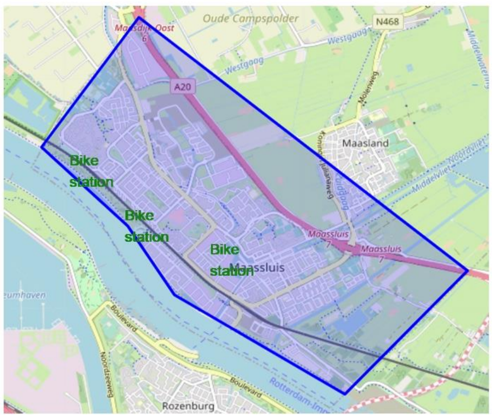
(a) Origins (green color) and destinations (red color) of passengers.




(b) Initial locations of scooters.



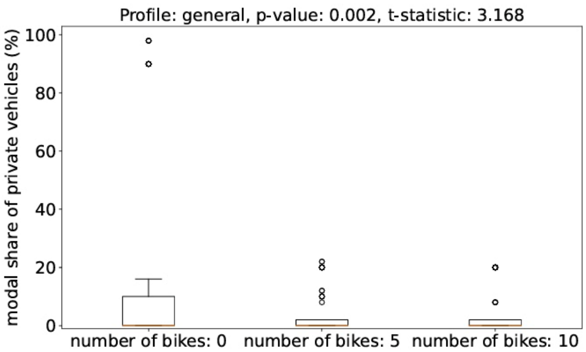

(c) Initial locations of ride-pooling vehicles.



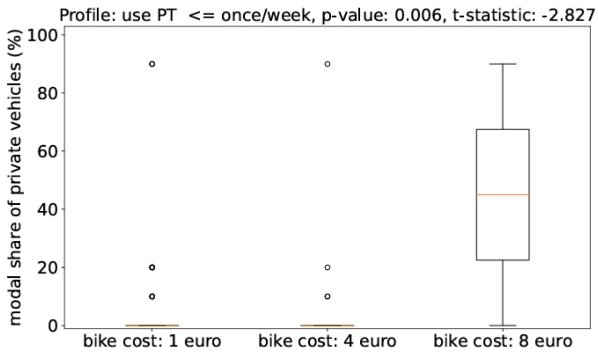

(d) Bike stations.

Figure 2: Requests and vehicles in Maasluis area, Rotterdam

Results in Figure 3, below, reveal that increasing the availability of shared micro-mobility options, such as bikes and scooters, significantly reduces the modal share of private vehicles across various user profiles. Specifically, more bikes lead to lower car use among general users, while high bike costs discourage adoption among infrequent public transport users, highlighting the importance of affordability. Shared scooters consistently reduce private vehicle reliance across diverse socio-demographic segments, including commuters, younger users, and those with lower incomes, suggesting their broad effectiveness. These findings emphasize the value of strategically managing fleet size and pricing to encourage sustainable travel behaviour and inform demand-responsive, equity-aware mobility policies.




(a)

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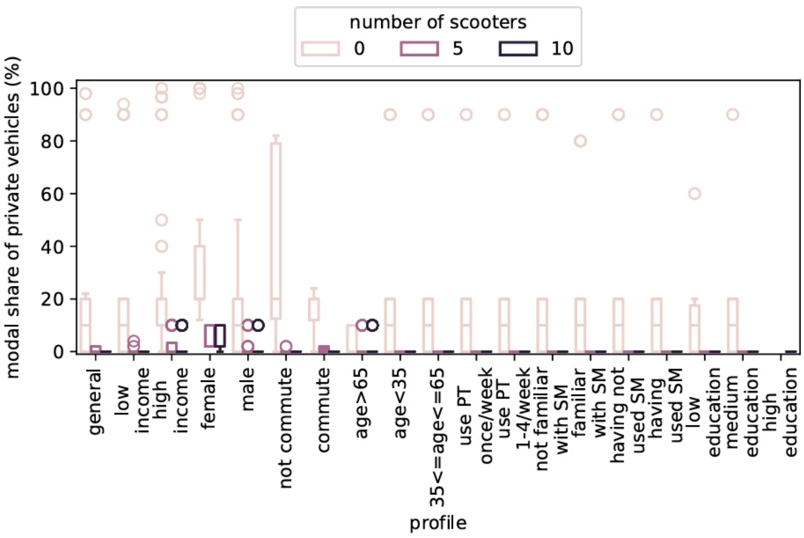



(c)

Figure 3. Modal shares of private vehicles

We also propose a novel dynamic fleet management model for urban electric waterborne transport systems that serve both passenger and parcel demands. Using a rolling horizon approach, the model dynamically adjusts vessel routing in response to real-time requests, integrating a mathematical optimization framework with an efficient insertion heuristic. The study applies this framework to Fredrikstad, Norway, where abundant waterways and emerging shared electric ferry infrastructure offer a testbed for mixed-purpose fleet operations. Comparative experiments demonstrate that mixed-purpose vessels—capable of carrying both passengers and parcels—outperform fixed-purpose ones by reducing empty travel distance and increasing the request fulfilment ratio without significantly increasing total travel distance. The findings suggest that integrating mobility and logistics on urban waterways enhances service efficiency and sustainability, offering practical insights for cities pursuing multimodal, low-emission transport solutions. This study has been published in the *npj Sustainable Mobility and Transport* journal.[1]

In addition, we are developing a demand-responsive scheduling framework that integrates Autonomous Surface Vessels (ASVs) with land-based fixed-route bus systems using the data from Fredrikstad LL. The study targets dynamic, real-time coordination under uncertain and fluctuating demand in urban water-land transport networks. To address the complexities of synchronizing ASVs with fixed bus timetables, the research adopts a Multi-Agent Reinforcement Learning (MARL) approach, where each vessel is modelled as an agent making decentralized decisions. Key objectives include minimizing passenger transfer wait times, improving system throughput, and optimizing energy efficiency. A simulated environment reflecting realistic spatiotemporal demand, battery constraints, and fixed bus schedules will be built using MARL toolkits. This work aims to enhance the adaptability, scalability, and performance of multimodal transport systems, particularly in cities with underutilized inland waterways. The outcome will come in year 3 of the project.

**Open-access code of the tool:** https://surfdrive.surf.nl/files/index.php/s/9yWnnu1ADGDfZc7

**Technical information:** https://arxiv.org/abs/2502.14528

**Technology-readiness level: TRL 4 – Lab validation of technology**

The multimodal trip planning tool is at TRL 4 because it has been validated in a lab environment using real-world transport network data, demonstrating integrated functionality of the optimization algorithms. However, it has not yet been tested in a live operational setting with real-time user interaction.

## 3.2 Fleet optimisation for new shared modes integrated with public transport

Our second mobility scenario assumes that fleet sizes for NSM and PT are also subject to optimization. In this case, a full social welfare function is presented, in which users' preferences are taken into account to optimize fleet sizes for NSM and PT, with an application to the case of bike-sharing and public transport. This is possible with a full social welfare function that incorporates not only users' benefits, but also operators' profit (total operator revenue minus total operator cost) for both NSM and PT and two additional components related to positive and negative externalities of mobility, namely the health benefits from active mobility and climate change cost, measured as the social cost of carbon from motorised mobility.

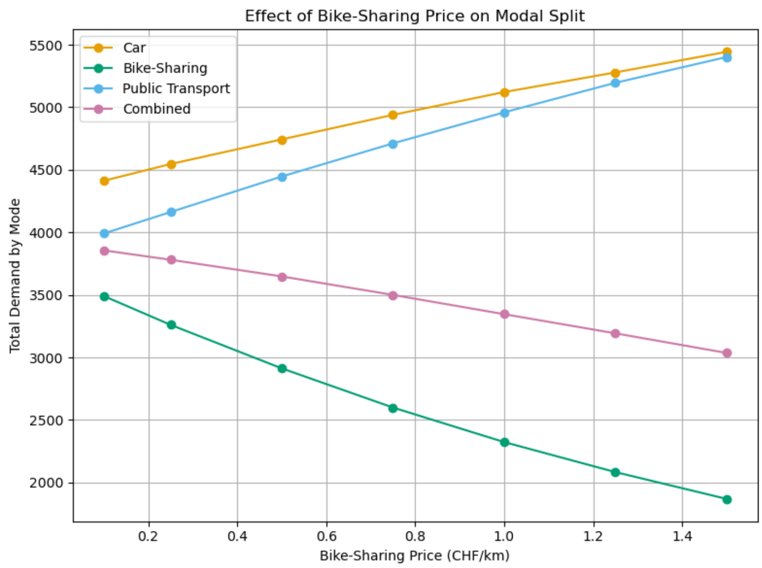
The framework, developed by the University of Twente, solved a bi-level optimization problem. The upper-level problem aims to optimize fleet sizing for both bike-sharing and public transport. The lower-level problem is a modified user equilibrium model, used to evaluate both route choice and mode choice by users within the network. The decision variables at this level are demand and traffic/passenger flows across different

[1] Miyoshi, H., Zhang, Y., Azadeh, S.S. *et al.* Dynamic fleet management of waterborne vessels with mixed passenger and parcel services. *npj. Sustain. Mobil. Transp.* 2, 16 (2025). https://doi.org/10.1038/s44333-025-00035-7

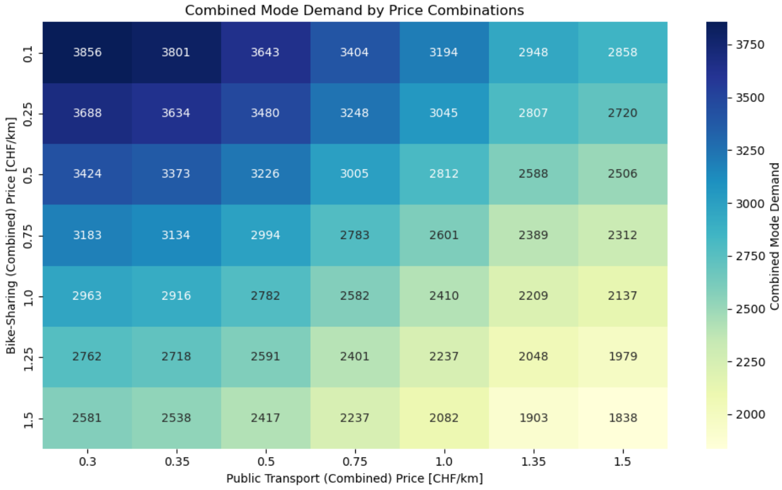
transportation modes. The upper-level problem is solved using a genetic algorithm, while the lower-level problem is addressed using a modified Method of Successive Averages (MSA). The lower-level model is embedded as a function within the upper-level algorithm, allowing both levels to be solved iteratively.

To test the reliability and effectiveness of the algorithm, we applied it to a well-known example from the literature: Mandl's network, which consists of 15 nodes and 29 links. The nodes serve as origins, destinations, and stations. Some input data — such as the OD matrix and free-flow travel times — are available in previous studies, while other attributes, including link lengths and capacities, were assumed by the authors. In addition, public transport lines were defined between OD pairs with higher demand, based on assumptions in the literature. Although Mandl's network is a conceptual example, it is useful as a first step to test our model and the concepts of service design integration between bike-sharing and public transport. The Mandl network is calibrated with cost and travel behaviour data from a single real-world region — Switzerland. This choice is motivated by the fact that during the third year of the SUM project we will extend our world to the real-world networks from the Living Labs Geneva in Switzerland and Munich in Germany.

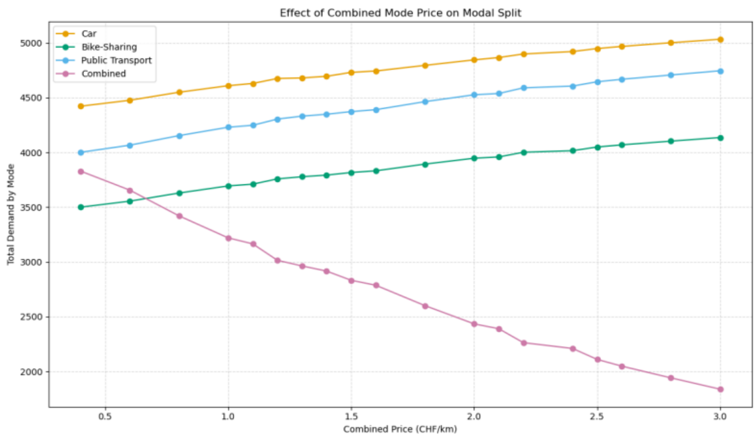
Figure 4 illustrates the effect of bike-sharing pricing on modal share distribution. To assess this impact, we analysed a range of bike-sharing price points (all the prices are CHF/km), for fixed car and public transport prices. Figure 4a assumes no integration in the system, i.e., the price of combined mode will be the summation of price of bike-sharing and public transportation.




(a) Impact of pricing for bike-sharing on modal split




(b) Impact of combined mode pricing on demand




(c) Impact of combined mode pricing on multimodal demand

Figure 4. Demand sensitivity to price variations with combined PT-BS

Next, we analyse the demand effects of changing the price of the combined public transport/bike-sharing trip when there is price integration. Figure 4.b shows a heatmap, the x-axis shows the public transportation price in combined mode and the y-axis shows the bike-sharing price in combined mode. This figure illustrates the price sensitivity in combined mode demand.

Figure 4.c illustrates the impact of pricing for combined mode on modal share in the whole multimodal system. The graph shows that how users change to alternatives when the pricing for combined mode trips goes up, keeping the prices for individual modes fixed. Figure 4.c shows that the rate of demand change for bike-sharing, cars, and public transport is relatively similar. This suggests that jointly optimizing the pricing of bike-sharing and the combined mode could lead to a more balanced modal share and promote a greater shift toward sustainable transportation options.

In the previous analysis of pricing and modal share, the availability of shared bike was considered fixed. Next we analyse the demand effects of different fleet sizing decisions for bike-sharing (availability of bikes at each station), for fixed prices for all modes. As it is evident from Figure 5, the demand for bike-sharing increases as the number of bikes per station increases, as a reflection of larger availability of bikes. Meanwhile, the demand for cars and public transport decrease, until a stabilised demand is reached for all modes, beyond which increasing the number of shared bikes plays no noticeable role on mode choice.

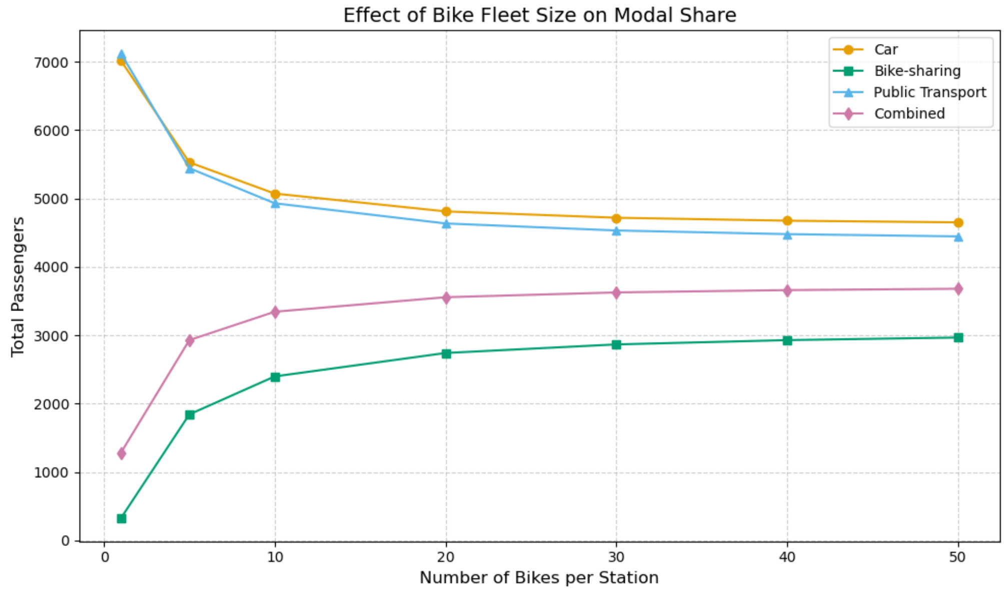



Figure 5. Impact of bike-sharing fleet size on modal share

While not shown in these figures, there is a clear trade-off between fleet sizing and pricing. The modal share of sustainable transport modes tends to increase with larger fleets and lower prices. However, striking the right balance between these factors is essential, as it reflects both operator efficiency and user satisfaction.

**Link to open-access code of the tool:** https://github.com/elham-mortazavi/BS_PT_Integration.git

**Technical information:** https://github.com/elham-mortazavi/BS_PT_Integration.git

**Technology-readiness level:** TRL 4 – Lab validation of technology

The BS-PT combined planning tool is at TRL 4 because it has been validated in a lab environment using real-world transport cost and user behaviour data, demonstrating integrated functionality of the optimization algorithms. However, it has not yet been tested in a live operational setting with real-time user interaction.

## 3.3 Designing service regions and fleet rebalancing optimisation for new shared modes

Our third step is the integration of design and operational decisions for NSM. In the case of modes like bike-sharing and scooter-sharing, fleet size decisions depend on rebalancing decisions, which were assumed fixed in the previous steps. In other words, smart and efficient fleet rebalancing algorithms can reduce not only operating costs, but also capital costs as fewer bicycles are needed to serve demand. We therefore tackle the problem of optimal repositioning decisions for bike-sharing systems (bike rebalancing problem – BRP), accounting for the cost of repositioning and the cost of leaving demand unmet due to lack of bicycles. The redistribution of the bikes takes place via a fleet of capacitated vehicles (trucks). A Mixed-Integer Linear Programming (MILP) algorithm, developed by the Technical University of Athens, is proposed aiming to minimize the total costs for a bike-sharing system, consisting of routing costs and unsatisfied user demand.

In an effort to improve the computational times required to obtain an optimal solution for larger-scale networks, a heuristic algorithm has been developed. The developed algorithm is capable of deriving high-quality solutions in short computational times for medium and large-scale problem instances. The output of the heuristic was then used to generate a warm-starting technique of providing an initial feasible solution to the solver before starting the optimization process. The model takes as input the geographical distribution of stations and the available fleet of trucks, and therefore, it is useful to analyse the influence of different configurations of the geographical distribution of demand, stations and bikes into the performance of the whole system.

To assess the solution quality with respect to the geographic distribution of bike-sharing stations, a set of problem instances is introduced (Data Set II), which consists of graphs where the total number of bike stations was deducted from the set O = {12, 15, 20}. We consider a homogeneous vehicle fleet with two vehicles available for the repositioning of the bikes. Finally, different distribution network classes are examined with respect to the geographical distribution of the bike stations. In particular, we distinguish among three geographic distribution classes: i) Random (R), ii) Random-Clustered (RC), and iii) Clustered (C). Regarding the R class, the locations are randomly selected from a set of locations L. For the RC class, a number of locations are clustered, whereas for the C class, the stations are selected from a set L in a way that creates clusters. In addition, the depot has been selected to be located at central positions of the examined geographic regions. An illustration of the framework is depicted in Figure 6, which shows the different geographic distribution classes (Random (R), Random-Clustered (RC) and Clustered (C)) of a network with 20 station locations.

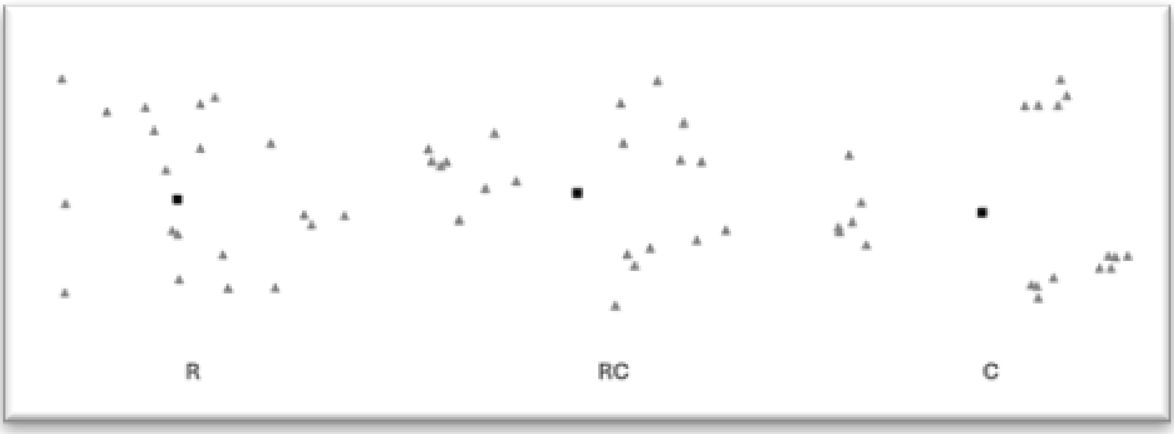



Figure 6. Different geographic distribution classes - Random (R), Random -Clustered (RC) and Clustered (C) - of a network with 20 bike-sharing station locations. Black square represents the depot.

A real-world application of the tool will be deployed in the Penteli Living Lab, in Year 3 of the SUM project. The municipality of Penteli issued a sustainable mobility plan in line with the sustainable mobility plan of the metropolitan area of Athens. Penteli's goal is to reconfigure completely the transport network by prioritizing sustainable mobility. To do so, additional mobility options are being offered to the residents and visitors of the municipality such as a bike sharing scheme. In order to ensure the connection between public transport services and shared mobility services, it is necessary to develop a tool capable of balancing he distribution of the available shared mobility fleet in the network, ensuring that shared modes are available at the right place (station). More specifically, taking into consideration the passenger demand variations, which will be obtained from historical data made available by Penteli, a rebalancing algorithm has been developed and will be applied in the city.

**Open-access code of the tool:** https://github.com/anikolopoulou/Fleet-Rebalancing-tool/tree/main

**Technical information:** https://github.com/anikolopoulou/Fleet-Rebalancing-tool/blob/main/Fleet%20Rebalancing%20Tool_Technical%20Report.pdf

**Technology-readiness level:** TRL 4 – Lab validation of technology: The fleet rebalancing optimization for new shared modes tool is at TRL 4 because it has been validated in a lab environment using real-world transport network data. It has not yet been tested in a live operational setting with real-time user interaction.

Next, we focus on the problem of defining optimal bike-sharing service regions that maximize demand coverage under the constraints of construction and operational budgets. Strategically located shared-bike stations can expand coverage, enhance accessibility, and reduce dependence on private vehicles, when integrated with the public transport network. However, limited resources (both capital and operational), such as constraints on bike procurement, station installation, maintenance, and re-balancing make it infeasible to satisfy all demand and require strategic prioritization. Furthermore, in real-world networks there is a coexistence of multi-modal and standalone trip needs: Stations must support both direct bike trips and connections to public transport. This dual role complicates sizing and capacity decisions.

The objective of the model is to maximize covered demand under resource constraints, including investment limitations on station infrastructure, fleet size and daily operational budget. We explicitly consider multi-modal travel patterns and multiple path possibilities for each origin-destination (OD) pair. By incorporating k-order shortest paths, we propose an integer programming optimization model. Our approach, developed by INRIA, prioritizes optimal paths for users while strategically allowing slightly suboptimal paths to enhance coverage and reduce operational costs (e.g., re-balancing). To solve the model, we employ a mathematical solver, Gurobi, and conduct initial tests on synthesized data. While the current version focuses on infrastructure planning and demand coverage, already integrated into the demonstrator as of Task 2.3, future extensions will more thoroughly consider the trade-off between operational re-balancing costs and additional demand coverage, to support more holistic and sustainable decision-making.

The methodology follows these key steps (Figure 7):

1. Input data pre-processing (for public transport network structure and user demand)
2. Network building and assumptions, as explained in the model paper
3. Decision criteria model, includes different parameters like budget, investment costs, and operational efficiency, multimodal accessibility (to enhance the connectivity within the network), the framework penalizes suboptimal routes
4. The output result is an optimized configuration of bike-sharing stations within the network. The bike inventory and capacity per station over different time periods is also provided

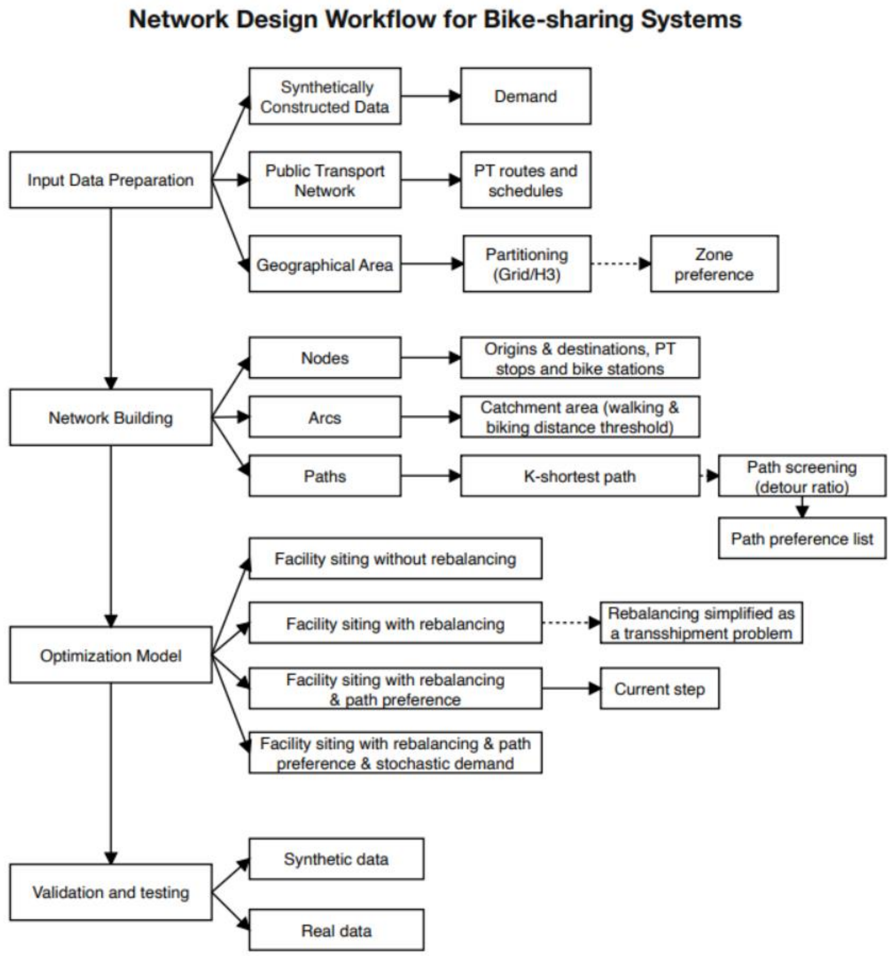



Figure 7. Network design work-flow for Bike Sharing Systems. The process followed to prepare the data and run the model

The demonstration scenario runs with the following configuration (figure 8):

- Grid 5 width, 5 height, a cell corresponds to a zone
- A zone has multiple public transport network nodes, corresponding to different line routes

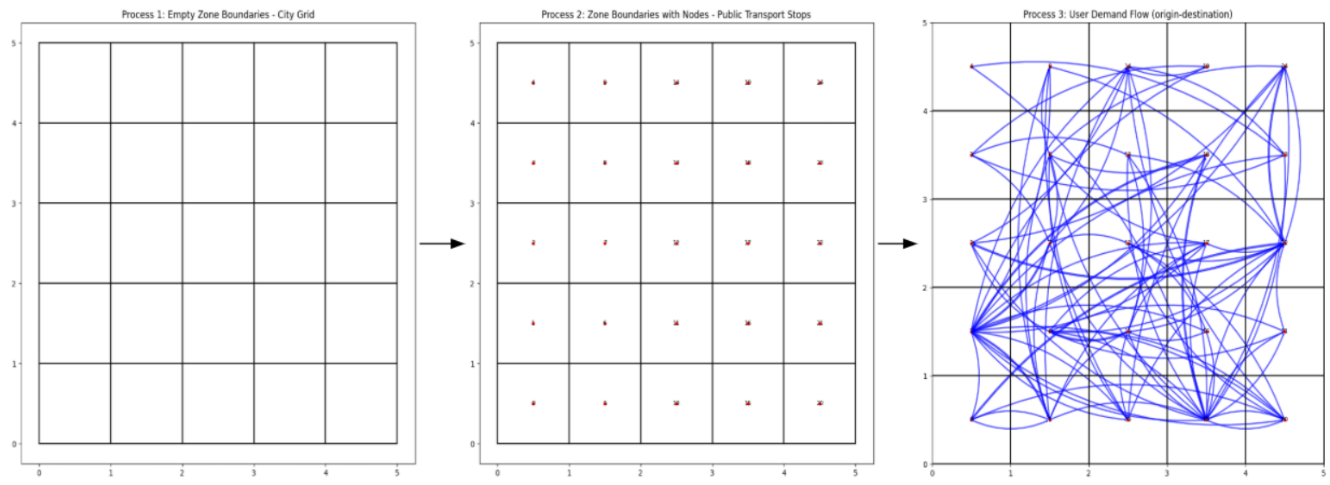


Figure 8. Network building process from Process 1 (grid creation), Process 2 (Network stops) and Process 3 (User demand visualization)

After pre-processing the data and running the model, the output is a network grid, with the new positions of bike sharing stations as in Figure 9. In the figure, the red stars represent a bike-sharing station, the tuple labels next to each station (*v*,*c*) denote the initial inventory (*v*) and station capacity (*c*), respectively, the blue lines represent predefined public transport routes and the directed arcs illustrate the average bike flow between stations over the operational period.

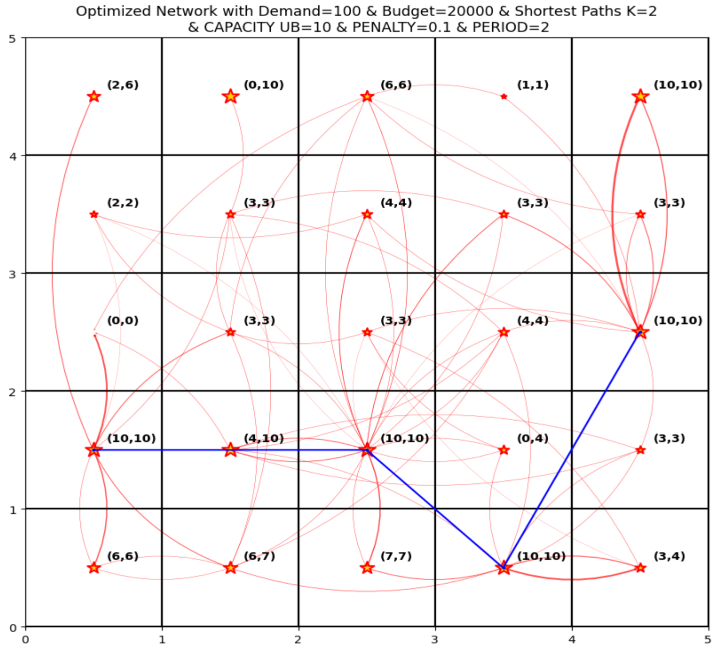



Figure 9. Resulting optimized network, with shared bikes stations positions in the grid, and its capacity

**Link to open-access code of the tool:** https://github.com/INRIA/sum-network-design-bike-sharing

**Demonstrator script with simple example**: https://github.com/INRIA/sum-network-design-bike-sharing/blob/main/simulation_demo.ipynb

**Demonstrator with test application for Geneva Living Lab**: future work in Year 3 of the SUM project: https://github.com/INRIA/sum-network-design-bike-sharing/blob/main/gva_demo.ipynb

**Technical information:** https://github.com/INRIA/sum-network-design-bike-sharing/tree/main/doc

**Technology-readiness level:** The current Technology-readiness level for this demonstrator is TRL 2 – Technology concept formulated: the preliminary model is developed and implemented, requires further iteration and experimentation.

It is expected to reach TRL 3 – Experimental proof of concept, since the current model will continue experimenting with simulation data. It has shown potential to prove how a network can be optimized, by defining new locations for bike sharing stations and its bike inventory and capacity.

## 3.4 Public transport rescheduling for a seamless integration with new shared modes

Previous tools on the integration of NSM and PT were developed under the assumption of fixed PT timetables, which are not re-optimized once an integration with NSM is implemented. We relax that assumption in our next step. Timetable synchronization for bus networks refers to the process of aligning the schedules of buses within a public transport system to optimize passenger transfers, minimize waiting times, and improve overall service efficiency. This is particularly important at transfer points or hubs where passengers switch between routes. The availability of NSM at the arrival of public transport vehicles is a key variable that interacts with public transport scheduling decisions. Timetable synchronization is essential for creating an efficient and user-friendly public transport network. It plays a critical role in improving service quality, enhancing connectivity, and promoting sustainable urban mobility.

As such, the bus timetable resynchronization problem considering passenger demand and in-vehicle passenger load is examined, in work developed by the Technical University of Athens. The goal is to (a) re-synchronize the timetable of bus lines to maximize the synchronized transfers at the transferring nodes (b) to maximize the number of the passengers benefiting from the synchronization and (c) to investigate the impact of in-vehicle passenger load on the perceived passenger travel times. The proposed tool builds on the bus timetable resynchronization problem and expands it by introducing the concept of generalized passenger travel times, which reflects how increased in-vehicle passenger load leads to longer perceived passenger travel times.

In Figure 10 an illustrative public transport network is shown. The network contains I = 2 bus lines with five bus stops for each line. The vehicle capacity is Q = 30 and the maximal value of deviation allowed from the departure times is equal to η = 1. Two of the bus stops are considered to be transfer nodes. The planning period is 60 minutes, the headway for each line is 15 minutes, and during the planning period, four trips per line are performed. In the initial timetable, the first trip of each line begins at the start of the planning period. The arrival times at each transfer node are determined by adding the bus running time from the depot to the transfer node to the trip's departure time. The travel distance between any two bus stops is provided in the squares above each link.

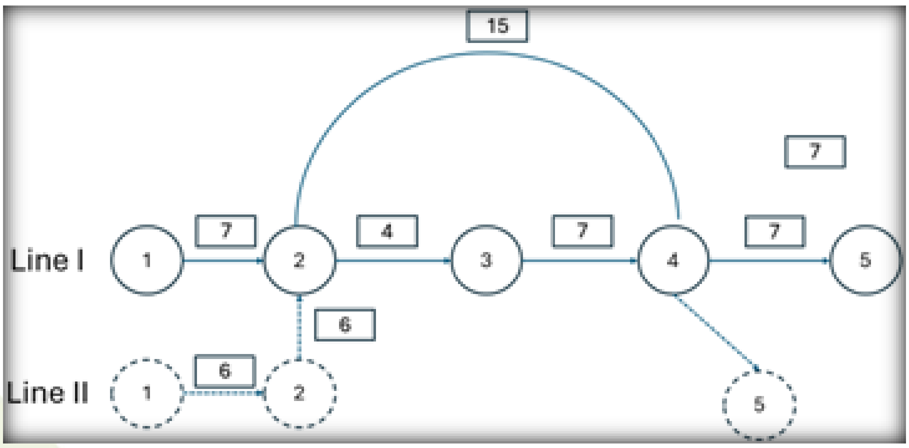



Figure 10. Illustration of an illustrative bus network demonstrating 2 lines with five stops in each one. Nodes 3 and 5 are the transfer nodes.

A real-world application of the tool will be deployed in the Penteli Living Lab, in Year 3 of the SUM project. The goal for Penteli is to create an integrated schedule for all bus service providers and complement it with alternative mobility options: both local Penteli buses and public transport services by OASA (the transport authority for the greater Athens region) will be optimized to satisfy the demand from, to and in the municipality of Penteli. Areas outside the catchment areas of public transport will be covered by alternative mobility options that will be taken into consideration by the optimization and the integration of schedules. The proposed PT rescheduling tool will re-synchronize the timetable of the local bus lines to maximize the synchronized transfers at the transferring nodes and to maximize the number of the passengers benefiting from the synchronization.

**Open-access code of the tool:** https://github.com/anikolopoulou/Public-transport-rescheduling-tool

**Technical information:** https://github.com/anikolopoulou/Public-transport-rescheduling-tool/blob/main/Public%20transport%20rescheduling%20tool_Technical%20Report.pdf

**Technology-readiness level:** TRL 4 – Lab validation of technology

The Public transport rescheduling tool is at TRL 4 because it has been validated in a lab environment using real-world transport network data. It has not yet been tested in a live operational setting with real-time user interaction.

## 3.5 Seamless integration of ride-pooling and public transport

Finally, we consider the integration of ride-pooling fleets and PT as well. In this case, we develop a framework that restricts some ride-pooling vehicles to arrive at a PT station shortly before the arrival of high-capacity PT services, to serve passengers that want to combine ride-pooling and PT. This model is developed in the Simulation Framework for Feeder Location Evaluation (SimFLEX). The utility of users with and without using the combined mode is assessed, therefore the framework could be used, on the one hand, to suggest optimal trip planning advice to users, and, on the other hand, to make decisions for the location of optimal transfer stations.

The Living Lab of Krakow planned to launch an on-demand bus service in one of 12 low-density areas (Figure 11), integrating it with public transport. During morning rush hour, small-capacity buses pool riders from designated pick-up stops and take them to high-frequency tram or train hubs. This aims to improve accessibility and address the first-mile challenge, but identifying the best implementation areas remains a key challenge.

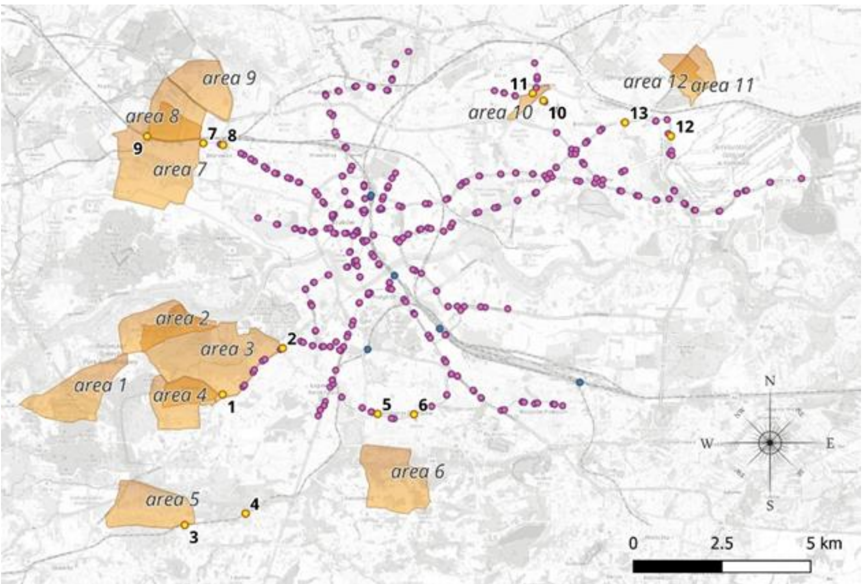



Figure 11. Krakow preselected areas (in orange) with corresponding hubs (in yellow), tram stops (in pink) and train stops (in blue).

In this work, Jagiellonian University proposes the SimFLEX methodology as a comprehensive decision-support tool developed to address the lack of location-specific methods for evaluating the potential impact and feasibility of novel transportation services. By leveraging spatial, socio-demographic, and transportation-specific data of the analysed region, the method enables the computation of various key performance indicators (KPIs) for a given area-hub combination, allowing a comparative analysis to identify the most suitable urban area for service implementation (see Figure 11). The proposed key indicators capture both operational aspects of the feeder buses, such as vehicle hours travelled, passenger-hours, and vehicle occupancy, as well as utility-based metrics that reflect the effectiveness of the overall transport system that includes feeders as first- or last-mile solutions. These are service attractiveness, waiting time reduction, and overall added value.

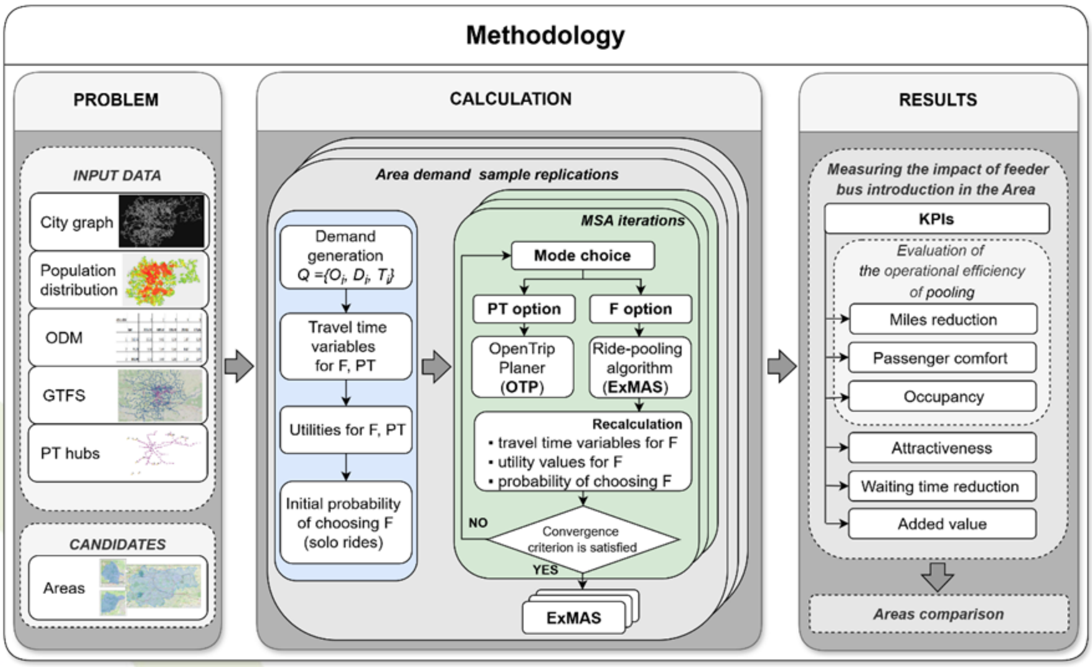


Figure 12. SimFLEX process to compute service performance

As described in Figure 12, for a given service area and hub location SimFLEX uses widely available inputs (such as network graph, GTFS, population distribution and OD-matrices) and runs a series of micro-simulations to obtain a wide range of performance indicators. First, the method samples microscopic demand pattern for services from macroscopic models. For each single demand realization, we simulate the travellers learning process, when they experience system performance (with unknown travel times due to detours, here sampled with ExMAS ride-pooling algorithm, see Figure 13). After stabilization (when each travellers expectations meet the realizations) we simulate extra runs to compute indicators from the stabilized system. This concludes a single run of SimFLEX, which can then be replicated (for different realizations of the demand), or used for comparisons (between areas, hubs, parametrization, etc.). Examples of spatial distributions of address points are presented in Figures 14 and 15.

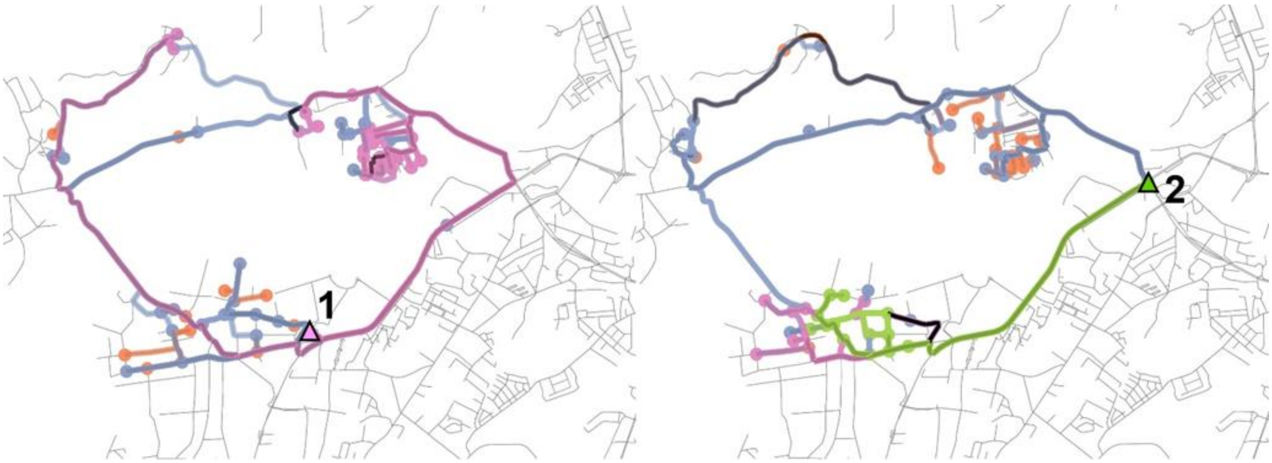



Figure 13. An example of visualising ride-pooling algorithm ExMAS shows sample rides for Area 3: all sampled travellers of an area are heading from origins (dots) to hub 1 (left pink triangle denoted 1) or to hub 2 (right green triangle denoted 2) as their transit destination points (hubs).

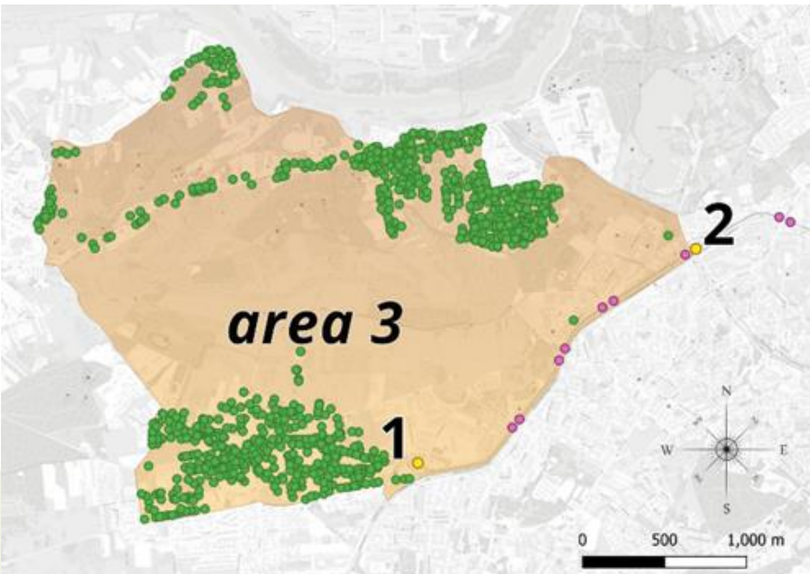



Figure 14. Example of the spatial distribution of address points (in green), tram stops (in pink) and light rail hubs (in yellow) for Area 3.

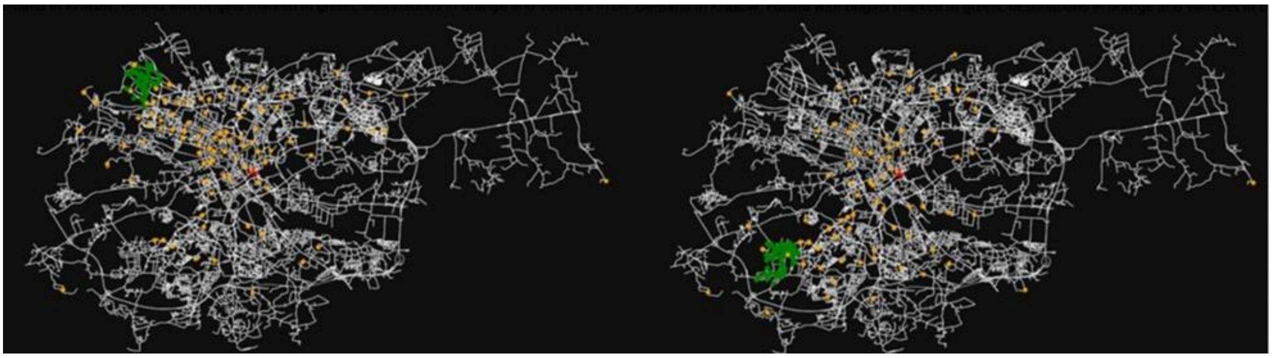


Figure 15. Sample example with address points (green) and randomly selected destination points (yellow) for the Areas 8 (left) and Area 3 (right).

Beyond evaluating feeder service effectiveness, SimFLEX provides an approach for comparing different urban areas (Figure 15), ensuring that services are introduced where they offer the highest benefits. Additionally, the methodology enables a sensitivity analysis of key performance indicators, which assesses the reliability of results under varying assumptions and model parameters. To achieve these objectives, SimFLEX integrates a combination of computational tools, optimization techniques and analytical methods that together enable a comprehensive assessment of feeder system performance.

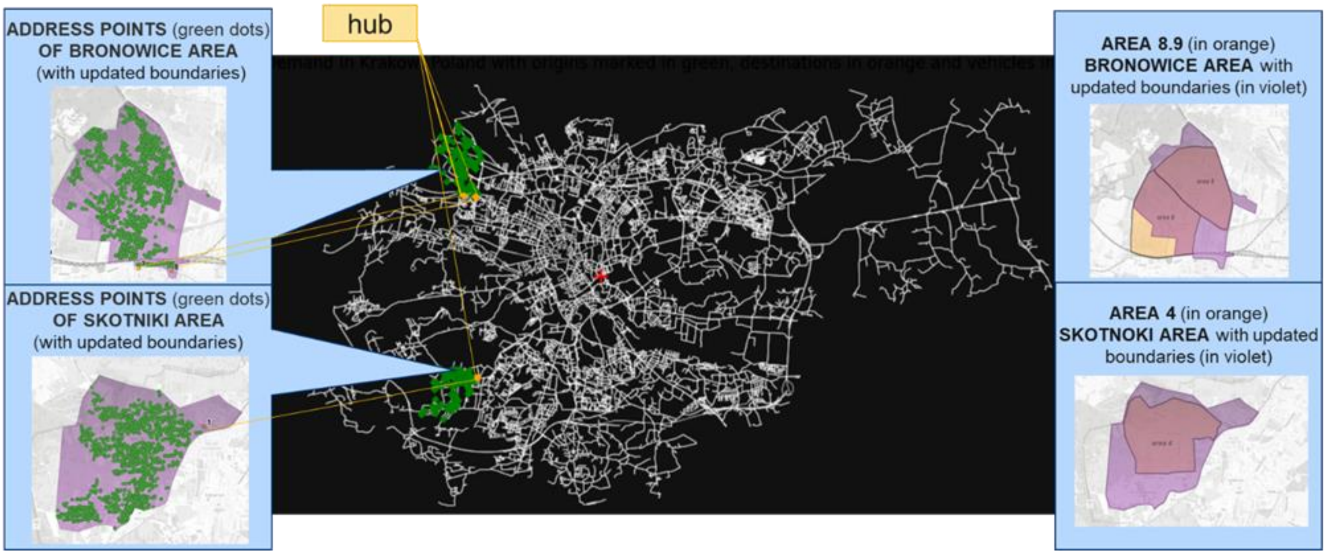



Figure 16. Updated Bronowice and Skotniki areas with marked address points (green) and hubs (yellow)

Figure 17 shows a sample route obtained using the OTP (Trip planning software) integrated into our developed framework. The trip planning software OTP is used for public transport trip planning for integration of feeder buses with public transport networks. It serves as a public transport routing tool, incorporating different transport modes, such as buses, trains, trams, etc. The OTP tool generates optimal routes based on real-time and scheduled transit data, considering travel time, number of transfers, and walking distances.

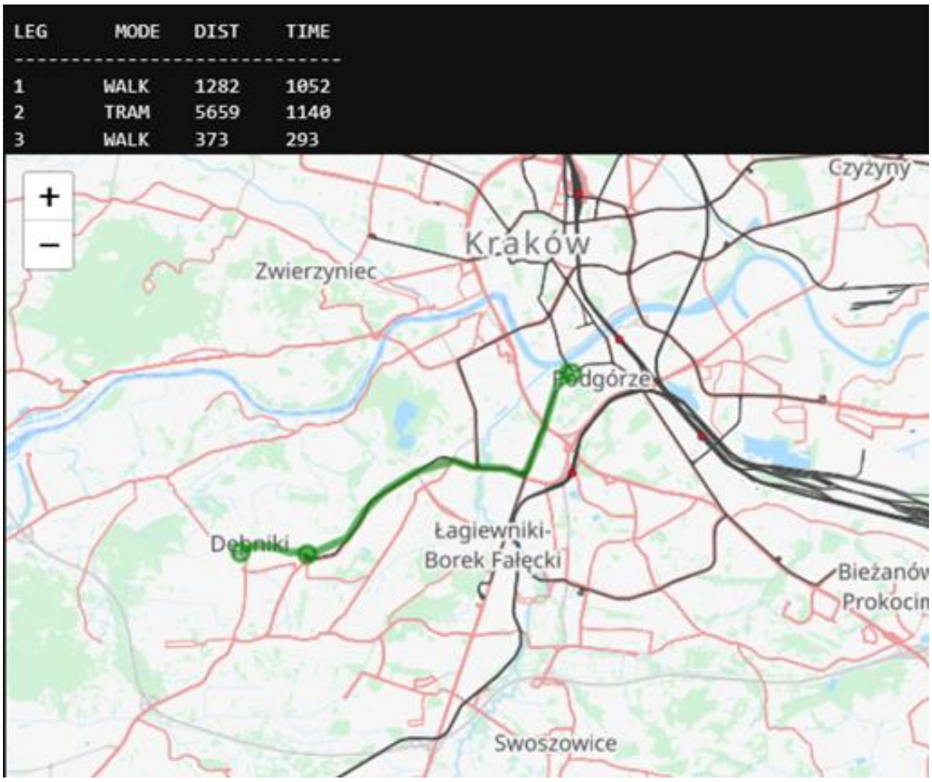



Figure 17. Visualization of a sample route obtained using the OTP (Trip planning software)

**Open-access code of the tool:** https://github.com/anniutina/SUM

**Technical information:** https://ssrn.com/abstract=5221622

**Technology-readiness level:** TRL 6 – Prototype demonstrated in a relevant environment

SimFLEX qualifies as TRL 6 – Prototype demonstrated in a relevant environment because it has been fully developed and tested using real-world data from Krakow within the SUM project, allowing for a practical evaluation of its functionality. The methodology has successfully computed key performance indicators and provided valuable recommendations for identifying optimal locations for feeder services.

An alternative approach has been implemented in the Jerusalem Living Lab**.** The SUM Simulation-Optimization Framework (Figure 18) was developed by researchers from Tel Aviv University (TAU), in order to find promising NSM designs. It incorporates three special-purpose modules. The modules permit (1) estimating traveller mode split in an existing transportation system with a new (hypothetical) NSM option, (2) evaluate NSM performance via simulation, and (3) optimizing the NSM to meet user-definable criteria. The base version of the framework relies on Biogeme, a discrete choice modelling package, FleetPy, the simulation framework developed by the Technical University of Munich and a new optimizer from TAU.

Two main Python scripts, *outer_loop.py* and *inner_loop.py*, call upon these modules. The outer loop is the optimization layer. It designs a NSM and calls the inner loop for evaluation. The inner loop is the simulation layer. It determines how many travellers choose each travel mode and how well the NSM performs, returning its evaluation to the outer loop. Then, the process starts again. The outer loop uses the previous evaluations to intelligently determine the details of the next NSM to try. This continues until the outer loop's stopping rule triggers.

A NSM design describes all the details of a service and how it operates. This includes the size of the fleet, kinds of vehicles, NSM ticket cost, etc. Each detail is called a parameter. The framework focuses on exploring NSM parameter combinations, assuming other modes remain constant. It relies on a user-supplied model for calculating the relative utility (attractiveness) of each mode. If new users lack such a model or any other required input, the framework's documentation offers advice and references.

We have piloted the framework on data from the Jerusalem Living Lab, for the design of a ride-pooling system. We have checked the results against external data sources and in discussions with LL team members and other city professionals. To illustrate our approach, Figure 19 shows the Yuvalim-Ganim Living Lab within the City of Jerusalem, in particular, how a local NSM service can be defined through the origin-demand matrix.

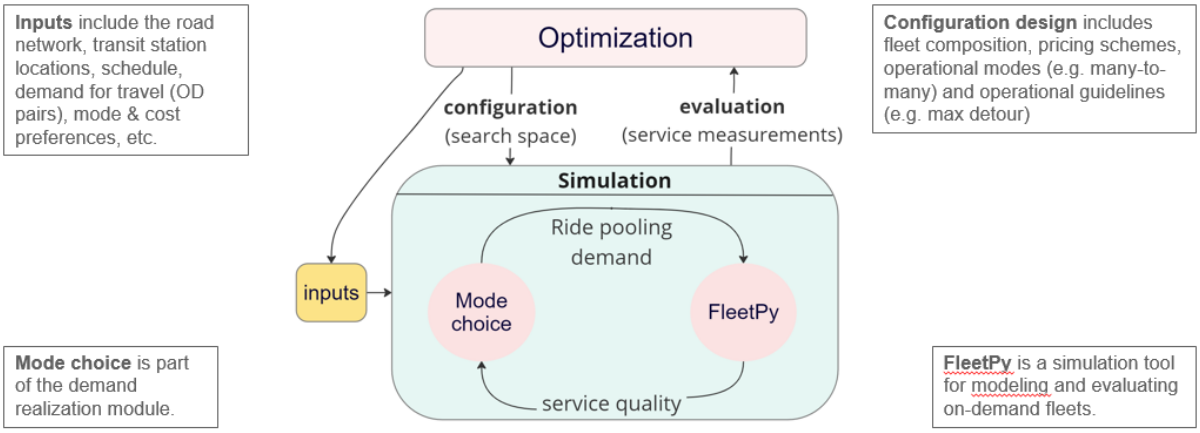



Figure 18. Overview of the SUM Simulation-Optimization Framework

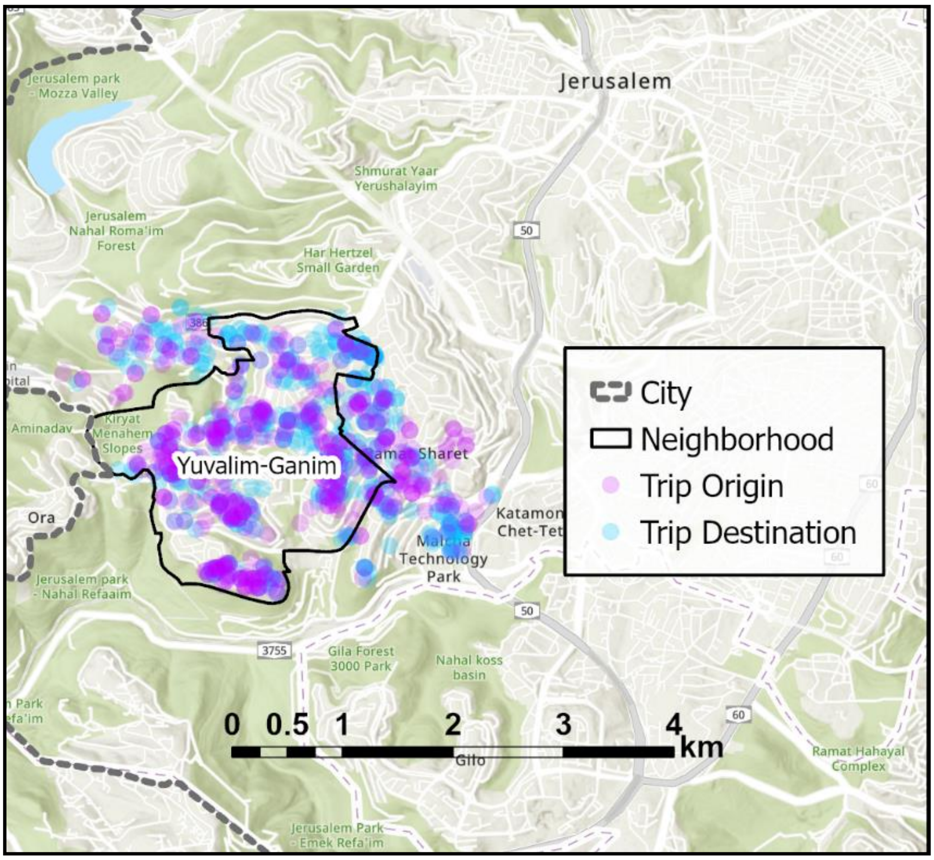



Figure 19. The Yuvalim-Ganim Living Lab within the City of Jerusalem

Figure 20 shows how the extremely low fee (2-shekels) for the NSM (mode 4) resulted in high demand that quickly dropped to a more manageable level over 20 iterations. Travelers left the system due to the initially low acceptance rate (high risk of *not* being picked-up), which converged at around 84% of requests accepted (see Table *1*. Summary Results for Six NSM DesignsTable *1*). Travellers switched to the other modes (0 = walk, 1 = bike, 2 = car, 3 = public transport).

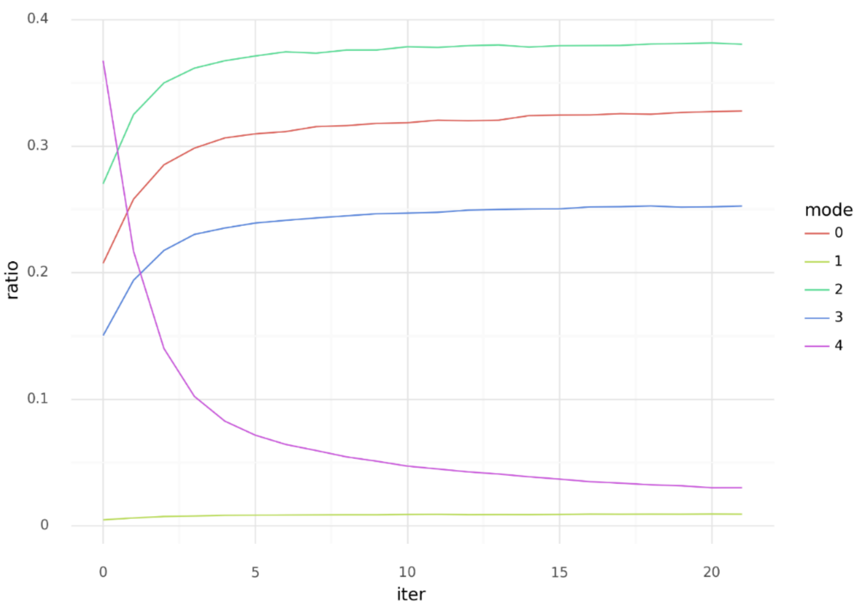


Figure 20. NSM Mode Split Convergence for 20-Vehicle Fleet & 2-Shekel Fee

| Fleet | Cost(₪) | Walk | Bike | Car | PT | NSM | Served | Acpt. Rate | Occ | Wait(min) |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 2 | 5,384 33.70% | 147 0.92% | 6,207 38.86% | 4,163 26.06% | 73 0.46% | 63 | 86.37% | 0.77 | 2:54 |
| | 20 | 5,386 33.71% | 151 0.94% | 6,238 39.05% | 4,181 26.17% | 19 0.12% | 19 | 98.59% | 0.66 | 2:22 |
| 10 | 2 | 5,317 33.29% | 147 0.92% | 6,157 38.54% | 4,137 25.90% | 216 1.35% | 175 | 81.02% | 0.96 | 3:10 |
| | 20 | 5,382 33.69% | 153 0.96% | 6,222 38.95% | 4,202 26.30% | 15 0.10% | 15 | 99.88% | 0.72 | 1:50 |
| 20 | 2 | 5,235 32.77% | 146 0.92% | 6,077 38.05% | 4,035 25.26% | 480 3.01% | 402 | 83.71% | 1.09 | 3:19 |
| | 20 | 5,367 33.60% | 149 0.93% | 6,242 39.08% | 4,196 26.27% | 20 0.13% | 20 | 99.86% | 0.79 | 1:13 |

Table 1. Summary Results for Six NSM Designs

In March 2025, the TAU team used the framework to estimate the mode split and performance of several NSM designs and presented the results to the Israeli Ministry of Transportation. The next version of the framework (Year 3 of the SUM project) will feature combined public transport/NSM trips and policy options for emphasizing mobility hubs and increasing ride pooling.

**Open-access code of the tool:** https://github.com/AUTOlab-TAU/SUM-Optimization

**Technical information:** https://github.com/AUTOlab-TAU/SUM-Optimization

**Technology-readiness level (TRL):** TRL 4 – Lab validation of technology

The SUM framework is at TRL 4 because it has been validated in a lab environment using real-world transport network data. It has not yet been tested in a live operational setting with real-time user interaction. A proficient Python programmer can setup a use case and receive actionable estimates for the mode split and performance of a point-to-point ridepooling service.

The Jerusalem framework relies on the simulation model FleetPy, developed by the Technical University of Munich (TUM). TUM has enhanced FleetPy's capabilities for simulating multi-modal travel in several key ways. First, a public transport routing module was introduced, written in C++ and based on the RAPTOR (Round-Based Public Transit Routing) algorithm. This new module enables efficient queries for the fastest public transport journey plans between any two public transit stops within a city.

Second, a Broker module has been added to allow communication between public transport and on-demand service providers. The Broker module processes user requests by breaking them down into different sub-requests based on travel mode segments. It then distributes these sub-requests to the appropriate service operators, which include both public transport and on-demand service providers. After receiving offers from these operators, the Broker combines them to generate comprehensive travel plans that are delivered to users.

In addition to basic on-demand requests, users can now specify public transport stops and the types of feeder services they need to create more complex multi-modal travel requests. FleetPy supports the simulation of three types of feeder services, using on-demand services such as first-mile, last-mile, or first-last-mile connections. To encourage the use of public transport, FleetPy provides users with direct public transport travel options for all requests.

This new functionality has been validated using synthetic data developed internally. In Year 3 of the SUM project, the system will be deployed in the Geneva LL, where it will utilize real-world data to simulate the integration of public transport and on-demand services in Geneva. This deployment will facilitate more comprehensive and nuanced scenario studies to evaluate the performance and impact of multi-modal transport solutions.

**Open-access code of the tool:**
FleetPy GitHub repository*: https://github.com/TUM-VT/FleetPy

**Technical information:**
1. The RAPTOR algorithm: https://www.jstor.org/stable/43666760
2. The C++ implementation of the RAPTOR algorithm**: https://github.com/mariaarabelo/RAPTOR

**Technology-readiness level (TRL) of the tool:**
This functionality is validated using internally developed synthetic data, confirming its effectiveness and comprehensiveness. In the near future, specifically at the end of 2025 or the beginning of 2026, the framework will be deployed in the Geneva LL. This deployment will utilize real-world data to simulate the seamless integration of public transportation and on-demand mobility services. By applying the Geneva LL use case, TRL 7 is expected to be achieved.

# 4 Conclusions

In this deliverable, we have described a series of tools developed as part of Task 2.3 “Coordinating the operations of shared modes and public transport”, to address interlinked problems in the general challenge of integrating new shared modes and public transport in an efficient, attractive and sustainable way, with applications to our Living Labs. The modes included in our quantitative methods are public transport (bus, ferry and rail based), bike sharing, scooter sharing and ride pooling. Current and future applications to the cities of Rotterdam, Munich, Geneva, Athens, Fredrikstad, Jerusalem and Krakow were described and shown with visual representations, when appropriate.

At present, month 24 of the SUM project, no Task 2.3 tool has a full-scale real-world application with TRL 7 so far. Currently, TRL 6 is the highest technology-readiness level reached in Task 2.3. The 24-month time for Task 2.3 proved to be too narrow to reach that level of application, as the set of tools required substantial scientific work in their development. SUM partners are working to reach TRL 7 applications in Year 3 of the project, which will be then reported as part of the final deliverables of Work Package 4; NTUA/Penteli will set up a process to make sure that the interrelated tools composing the “Scheduling integration tool” will reach the target TRL 7 by Month 36. An application of a combined public transport/shared mobility design from a Task 2.3 tool would indeed influence some of the Key Performance Indicators outlined in WP1, and would therefore be shown in the Open Data Platform (Task 1.5).