Planning and Visual Tools for an optimal linking of On-demand services & Public Transit

Towards a Sustainable and Inclusive Mobility

Corrado Muratori

Conference paper April 2023

STRC | 23rd Swiss Transport Research Conference
Monte Verità / Ascona, May 10-12, 2023

STRC 2023 conference paper

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Corrado Muratori
Zurich University of Applied Sciences (ZHAW) - IDP
Technikumstrasse 81, 8400 Winterthur, Switzerland
Phone: +41- 779 709 263
E-Mail: muaa@zhaw.ch

In collaboration with Universität Zürich (UZH) – GIVA

Supervisors: Dr. Stephan Bütikofer, Prof. Dr. Sara Irina Fabrikant

April 2023

Abstract

My Ph.D. project aims to create tools that can help implement on-demand services in synergy with traditional public transit. This transport integration is geared toward shifting the modal split in low-demand areas from individual transport to public transport, addressing issues such as environmental sustainability, accessibility, equity, service quality, and economic sustainability. The tools created will allow a classification of geographic zones to be displayed on GIS according to their potential for on-demand services (based on economic sustainability and modal shift). These outputs will be interconnected with a demand model and an integrated planning method, in which the settings of the on-demand services configurations will be entered as input variables. This connection will also make it possible to find the optimal configuration of integrated transport according to the territory's characteristics and the available budget. Based on a Poisson regression model, the demand model will be used to calibrate the agent-based model, implemented on MATSim, a simulation software. In this first phase of the project, the simulation model is implemented on the Swiss territory and the possible target areas will be identified in terms of housing density and current characteristics of the modal split.

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1 Introduction

Mobility policies in the last decade are finally moving towards a reduction in CO_2 emissions, but usually without a strategic integrated plan.

It is important to understand that there is a long-term elasticity derived from the ability of people to adjust to policy measures. Road improvements tend to attract traffic, until the car is, on average, no more attractive than transit, but by then, we will be in a new congested equilibrium with a more degraded transit, and everyone would be worse off. (Anthony Downs, 1992)

To reduce the congestion problem, therefore, society's target must be overcoming private commuting (or at least decreasing it).
To create a valid alternative to private commuting, 2 of the main solutions are identified in:

1) Creating on-demand services to replace the current bus, to intercept some of the routes for which citizens prefer private transport (Alonso-González et al., 2018; Burrieza, 2019; Koh et al., 2018; Shaheen & Cohen, 2020).
On-demand service (in the literature also referred to as Dial-A-Ride or taxi-bus or demand responsive transit (DRT) or Ride-Hailing) is a Demand-Responsive transport, an advanced, user-oriented form of public transport characterized by flexible routing and scheduling of small/medium vehicles operating in shared-ride mode between pick-up and drop-off locations according to passenger's needs (Interreg Europe, 2018).

On-demand service can update his lines, routing and scheduling in real time to accommodate the varying demand of people, for example accessing or egressing big events.

2) Creating continuity between the mobility measures and services (Mobility as a Service) (Krizek & Stonebraker, 2011; Sochor et al., 2018)

The main idea behind M.a.a.S. is to provide travelers with customized solutions based on their specific travel needs. Through a smartphone app, for example, a user can purchase a ticket that includes access to on-demand transportation to the nearest high-frequency station, followed by train travel to the city, and finally a shared micro mobility option to reach their destination, all covered by a single ticket.

In Switzerland in particular, where I will apply my developed models, public transport is highly customer-oriented in many geographic areas where it can operate with sufficiently high economic efficiency due to high line utilization.

In more sparsely populated rural areas, the extent of spatio-temporal demand decreases, and so does the economic efficiency of high-frequency lines. In addition, the distances between stops increase due to the greater spatial extent of rural areas. This, in turn, forces transit agencies to reduce line frequencies to attract enough passengers, or to reduce the number of stop locations in order to ensure line turnaround times and thus operate lines economically. As this effect leads to a lower attractiveness of public transport, many people end up using their cars. The car ownership rate increases and the modal split shifts from a higher share of public transport to a much higher share of private transport. This effect can e.g., be seen with the so-called modal accessibility gap (MAG) between two modes of transport $m1$, $m2$ for a specific location ii, which is defined by

$$MAG_i(m_1, m_2) = \frac{A_i(m_1) - A_i(m_2)}{A_i(m_1) + A_i(m_2)} \in [-1, +1]$$

and which is illustrated for the city of Winterthur in figure 1 for the accessibility $Aii(m1 = car)$ and $Aii\ (m2 = PT)$ at location ii = station of Winterthur.

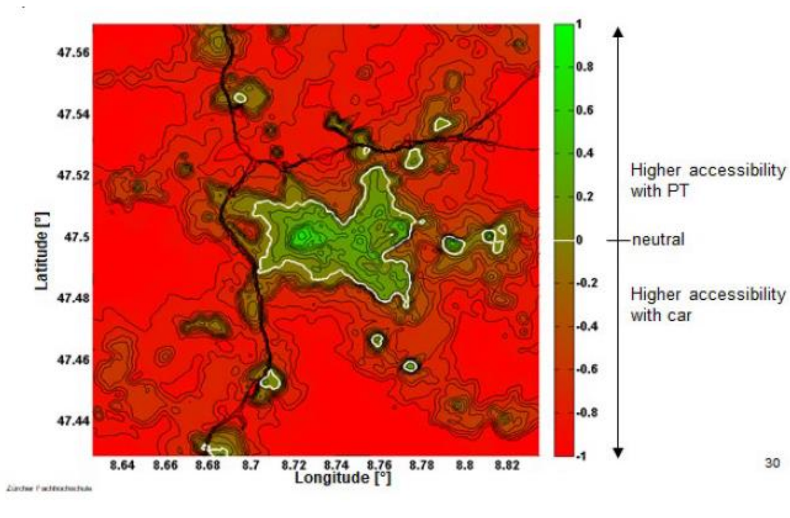

Figure 1. Modal accessibility gap between public transport (PT) and cars for the city of Winterthur. Trips to external cities, morning peak 07:00 to 08:00 (Steiner, 2016).

In this work, I will focus on how on-demand services could be implemented, defining a methodology that allows finding the best possible setting to fit them in the M.a.a.S. context, focusing on the multi-modal hub that would connect rural areas to urban areas, thanks to on-demand buses.

In the project I will model public transport and on-demand transit together aiming at solving the lack of flexibility in public transport. It is not feasible to operate on-demand buses cost-effectively in the private sector, as has been shown, except for specific routes, or with autonomous mobility. So, the approach will also require the consideration of integrated public-private management policies, which make these expansion processes economically feasible.

2 Related Work

2.1 Constraints and Assumptions in the Vehicle routing problem

In this work I will not go into detail on the algorithms for optimizing the movements of the on-demand bus fleet, but I will use these algorithms to perform or simulate the operation of the service. Also, I'm going to determine the best possible configuration, depending on the chosen territory. This configuration is characterized by constraints and parameters for which it is useful to know the theory of optimization software. In this section I will briefly introduce these components, referring to the first algorithms, which have become more complex in recent years with the extension to the dynamic problem (with travel times that vary over time).

Jaw in 1986 built a precisely constructed structure for a time-constrained version of the advance-request, multi-vehicle, many-to-many Dial-A-Ride problem (Jaw et al., 1986).

In the algorithm, the time constraints can split into two kinds: a) the amount of time by which pick-up or delivery of a customer can deviate from the desired pick-up or delivery time; b) the time that a customer can spend riding a vehicle (which can be a percentage threshold in comparison with the minimum time). The algorithm uses a sequential insertion procedure to assign customers to vehicles and determine a possible schedule for each pickup and delivery. The entire organization is regulated by an objective function that balances the cost of providing service with the customers' preferences for pick-up and delivery times as close as possible to those requests (Psaraftis, 1980, 1983).

Dial-A-Ride algorithm relies on the following assumptions (mainly maintained in the newer software implementation too):

• The customers can specify the desired pick-up time (DPT) from an origin (O) or a preferred delivery time (DDT) to their destination (D). It is crucial to note that it is impossible to specify both.

• Customers who specified a DPT cannot be collected before that specific time.

• Customers who specified a DDT cannot be delivered after that specific time.

• Given an average riding time (ART) for any client, it must not exceed a maximum riding time (MRT). The MRT is computed based on the direct riding time (DRT) from an origin to a destination, representing the very minimum riding time without stops in between O and D.

• The difference between the desired time (DT) of pickup or delivery and the actual time of pickup or delivery, named deviation time (DV), must not be more than a set maximum.

The table below shows a summary of the principal variables:

N	Number of customers
m	Number of available vehicles
DPT_i (DDT_i)	Desired Pickip Time (Desired Delivery Time).
EPT_i (EDT_i)	Earliest Pickup Time (Earliest Delivery time).
LPT_i (LDT_i)	Latest Pickup Time (Latest Delivery Time).
APT_i (ADT_i)	Actual Pickup Time.
DRT_i	Direct Riding Time (Interval needed by vehicle to go directly from O to D)
ART_i	Actual Riding Time
D(x,y)	Time to get from x to y
[+i | -i]	Pickup (+) and Delivery (-) events
DV_i	Deviation time between desired time and actual time
WS_i	Maximum acceptable deviation between desired and actual time
d	Number of stops within a block
$SLACK_j$	Waiting time interval before the next stops block j

Figure 2. Summary of the principal variables of an optimization software

These will also be used in the integrated planning optimization.

After a long period of algorithmic and software development in the field of on-demand service (Berbeglia et al., 2010; Cordeau & Laporte, 2007; El-Sherbeny, 2010; Gentile and Catta, 2004; Hu & Chang, 2015; Ropke et al., 2007; Schilde et al., 2011, 2014), in recent years, also thanks to new technologies such as mobile apps, we have moved on to studies more aimed at the application of this type of service.

In the rest of this literature search I will focus on the studies of this service integrated with public transport.

2.2 Integration between on-demand services and Public Transit

In this paragraph I will report the studies that have explored the potential for integrating on-demand services with public transit. Jung (2018) found that a combination of on-demand shuttle services and public transit can increase the accessibility and usability of public transit, especially in low-density areas. Another study found that integrating on-demand services with public transit can lead to cost savings for both the transit agency and riders (Zhou et al., 2019).

A study by Kontinakis (2018) examined the potential of integrating on-demand shuttles with public transit. The researchers found that such an integration could lead to reduced car ownership and increased use of public transit, resulting in benefits such as lower congestion and emissions.

Between these researches, the most important for my work is from Henken et al. , that proposed a detailed version for the first integrated dispatching system (Henken & Jedelhauser, 2018)

In their System, every citizen could go to the corner near his home and with a flexible on-demand transport be brought to the nearest access point of the public network. Based on the agent-based transport simulation framework MATSim, developed a model which allows simulating the desired system behavior, applied in Zürich, using an artificially created population.

Their kind of service requires many small, automated vehicles (AV), to be economically feasible. This solution is still too granular for human-driven vehicle. Furthermore, this paper doesn't include the budget conditions, and therefore leaves the current public transport network as it is. Finally, it doesn't aim for the best service configuration, but it takes it as given and checks how the system could work in this specific case (therefore doesn't aim for the optimal planning).

However, there are also challenges to integrating on-demand services with public transit. One challenge is the lack of coordination between the two systems, which can lead to inefficiencies and a less seamless experience for riders (Goh et al., 2020). Another challenge is the need to ensure that on-demand services are accessible to all, including those with disabilities (Budzier et al., 2020)

To address these challenges and optimize the linking of on-demand services and public transit, there is a need for effective planning. This can be reached with a planning optimization, that until now has been mainly carried out only for on-demand services, without taking into consideration the multi-modal chain.

2.3 Planning optimizations for On-demand buses

In bimodal ridesharing, an on-demand mobility service operator offers to drop off a passenger at a transit station, where the passenger uses the public transit network. Such collaborations with public transport agencies present a huge potential to increase the ridership. However, most existing studies on dynamic dial-a-ride/ridesharing mainly focus on mono-modal cases only. (Ma et al., 2018). There are a number of interesting research studies that have resulted in the current state-of-the-art when it comes to single-mode optimization of on-demand buses (Basu et al., 2018; Coutinho et al., 2020; Daganzo & Ouyang, 2019; Huang et al., 2020; M. E. , J. L. and P. S. Kim, 2019; X. Li et al., 2021; Mehran et al., 2020; Pinto et al., 2020; Wang et al., 2019; Winter et al., 2018).

In 2021 we had a first integrated planning optimization between a DRT and public transit. This work of Zhao et al. (2021) will also be the most important reference in my work to start building a planning algorithm. In their work, the terminal bus stops of regular bus lines, the service area of the DRT, and the fleet size of both regular transit and DRT are optimized simultaneously with the objective of minimizing the total travel time of passengers and the total fleet size. In the process, lines, stops, and fleet sizes, are determined, on the basis of the existing transit network.

The topological graph of the joint service is illustrated in Figure 3. In the context of this work, the original regular transit line can be shortened. The adjusted regular transit line serves all stops of a segment of the original regular transit line in both directions. However, the regular transit line can neither be extended nor a new line can be added.

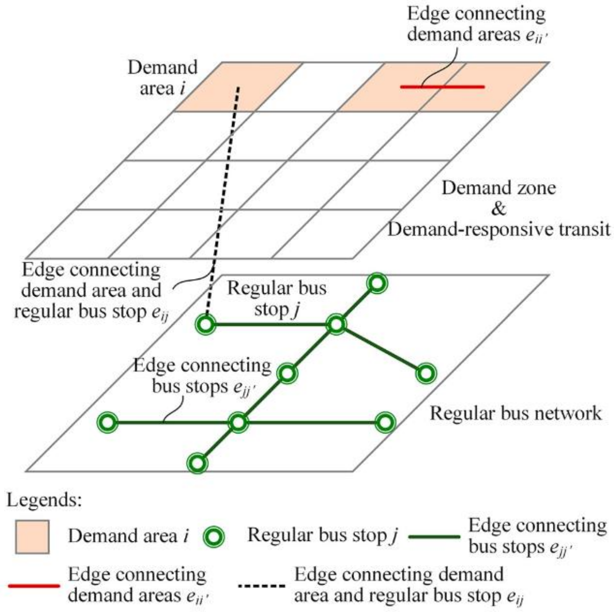

Figure 3. Topological graph of the joint service (Zhao et al. , 2021)

Here the variable dependency is missing in the computation of demand for the service (with the variables such as the ones described in the first paragraph of this section), that it will be necessary for calculating the economic efficiency. Furthermore, also this project doesn't consider properly demand-supply interactions, budget conditions and doesn't aim to find the best service configuration.

3 Research Gap and Goal

3.1 Research Gap

There are few works that already aim at integrating these two forms of transport, but they start from a specific service's constraints configuration and, given that, they make simulations to compute demand or level of service (Pinto et al., 2020; Sieber et al., 2019) . What is missing is a variable-dependent model that would allow to compute where the service is economically efficient, but also which is the demand or level of service in dependency of the service's setting parameters (pick-up time-windows, service's area, maximum allowed detour, etc.). This could be done adapting, to variable constraints, the algorithm proposed by Zhao et al. (2021).

The kind of on-demand settings that I will determine, will be comparable with the one described by (Henken & Jedelhauser, 2018). As it was described in the last section, they propose a dispatching system that is bringing users to the next bus stop, without changing the current public transport network. Their paper doesn't include budget conditions, that I will insert in the definition of the service, adapting the cost calculation software framework, defined by (Bösch et al., 2018).

3.2 Goal

My specific goal is, given a certain population, network and budget, to determine which is the best configuration of on-demand services, together with a technique of selection of current public lines that could be eliminated because of inefficiency. The target output of these new configurations would be a shift of modal split from individual/private forms of transport, to shared public ones.

To find the best integrated network design, it will be necessary to create models that allow simulations on MATSim (agent-based simulation tool) (Axhausen, 2016), using line planning methods adapted from Zhao et al.

This goal can be translated into the main **research question**: How can frequency-based services and on-demand services be optimally integrated in a public transport planning method? With which settings?

In the following paragraph it will be showed the structure of my work, that will provide the answers to this question.

4 Methods

The project activities are based on data analysis, integrated planning approaches of frequency-based services and on-demand services, agent-based simulation of stochastic mode choice as response to spatio-temporal demand patterns and its visualisation in geographical information systems (GIS).

To answer the research questions, the work will be accomplished with a 3-stage methodology. The approaches are based on known results from the literature or preliminary studies (Henken & Jedelhauser, 2018; X. Li & Quadrifoglio, 2010; Luzern -Wirtschaft Roger Sonderegger et al., 2018; Quadrifoglio & Li, 2009; Sieber et al., 2019; Zhao et al., 2021). These are to be consolidated and expanded so that a consistent methodology emerges. Below there will be a brief description of the research design and project modules.

4.1 Step 1) Classification of geographic zones according to their potential for on-demand services

The cited models (Kompetenzcenter Digitalisierung, 2022; X. Li & Quadrifoglio, 2010; Luzern -Wirtschaft Roger Sonderegger et al., 2018; Quadrifoglio & Li, 2009) provide economic, demographic as well as geographical indicators or thresholds to identify areas with and without potential for on-demand services. Costs computation

To include budget conditions and economic efficiency, I will need to adapt the cost calculation software framework, defined by Bösch et al. (2018).

To compare different real scenarios from a global point of view, it will be possible to compute the general cost. From the user's point of view, this is defined as: Cg = Cm + Ct + Cr + Cd where Cm is the monetary cost, Ct is the cost of the time spent, Cr is the cost of the risk taken during the movement, and Cd cost of perceived discomfort while moving (Ricci Stefano, 2011).

On the company's side, the overall cost is a sum of fixed and variable expenses such as crew, taxes, insurance, fuel, maintenance, and other items. There is also a general social cost, consisting of externalities that cause typical damage, such as accidents, noise, air pollution, nature and landscape, indirect effects of production, or urban effects. The calculations of these costs also depend on the methods and target chosen.

As regards the simulations of the service and the identification of the cause-effect mechanisms between supply and demand, I will use MATsim (Axhausen, 2016).

MATSim is a Multi-Agent Transport Simulation Toolkit. This open-source software is the global standard for agent-based simulations. The development of the software is carried out by a community with members from ETH, with whom I have already coordinated for a supervision on the training process.

In parallel, I will also extend the agent-based Demand-models of MATSim, to catch the rural areas patterns of dependency from the service's settings. I want to create this demand model in a way that allows obtaining the demand, following the service's budget and constraints inputs. This integration will give to the model a demand-supply interaction that will allow also to compute the economic efficiency of the proposed system.

4.2 Step 2) Integrated planning of on-demand and frequency-based regular services

The application of a unified transport system in rural areas is the core part of my project, and in this phase I will develop the theoretical bases that will define the algorithm for an integrated service planning. For this purpose, a model is to be developed with which the on-demand service and the regular service can be planned together (Schiewe et al., 2022; Zhao et al., 2021). In this step, I will also find which stops of the regular service are still served and which stops are served by the on-demand service and how users are going to access the regular public service. The simulation in MatSim thus also serves as a validation for the proposed integrated offer in a test area. The research will simulate on-demand bus approach by using Jaw algorithms, described at the beginning of the Literature review.

I will use the work of Zhao et al. (described in the section "Related Work"), making a step forward. In their work, the terminal bus stops of regular bus lines, the service area of the DRT, and the fleet size of both regular transit and DRT are optimized simultaneously.The core of the optimisation is a non-linear programming model to minimise the total travel time of passengers and the total fleet size. With my steps further, this algorithm will also allow to find the best possible service configuration being connected with the demand model that is used in the simulation.

Varying the budget conditions and services constraints, the planning will change and will cause a change in performance, and consequently on demand. This iteration will go on until an equilibrium between demand and supply is found.

For the simulation, MATsim can simulate the entire population of Switzerland as individual agents. For each agent, all mobility decisions are computed microscopically: from activity generation, tour construction, choice of destinations and travel modes, through route choice and network simulation. MATsim can simulate all modes of transport and also inter-modal chains.

The model allows us to evaluate mobility from a holistic perspective. The comprehensive and complex approach allows for a deeper understanding of why and when peaks occur, or how person attributes and transport service variables are influencing travelers' choices. The output it will composed by fully disaggregated network flows & indicators, such as LoS or accessibility.

I will apply the planning and demand methodology to a partition of the Swiss territory, that still must be defined.

The public transport data are 24-hour timetables, which are derived from SBB's nationwide rail model data. These will be combined with the integrated On-demand bus planning outputs. Then, I will use Synthetic Population data from BFS, created with census data, that since 2010 has been conducted annually by the Swiss federal office. Thanks to this population census system, economic and social change can be analysed effectively.

4.3 Step 3) Calibration & Validation

Despite the increased complexity of a microscopic and activity-based model, MATsim must satisfy the same calibration and validation requirements as conventional macroscopic models do. The calibration process it will be an iterative procedure which repeats the following steps:

1. Simulation of the full model
2. Validation of the simulation results by comparing them to empirical values
3. Assessment of the model quality based on various indicators

4. Calibration of model parameters, modification of input data and implementation of new software features.

The model will be validated in comparison to comprehensive travel statistics that include the national travel diary survey, commuter matrices, the national rail origin-destination survey, rail counts, other public transportation counts and road traffic counts.

To assess the model quality for calibration criteria consisting of numerous count data, I will use conventional error measures like % mean absolute error (%MAE) and % root mean square error (%RMSE), but also the scalable quality value (short: SQV, see (Friedrich et al., 2019)). The SQV ranges between 0 (no match) and 1 (perfect match), where is excellent for SQV≥0.9 and sufficient for SQV≥0.7.

It is expressed as shown in the formula:

$$g_{SQV} = \frac{1}{1+\sqrt{\frac{(m-c)^2}{f \cdot c}}}$$

Where m is the model value and c is the counted value. f is a scale factor and depends on the type of the counts. Calibration criteria consisting of numerous count data and its objective is to maximize the number of counts with a good SQV.

The following picture shows an example of validation based on Swiss rail stations' count of passengers' flows.

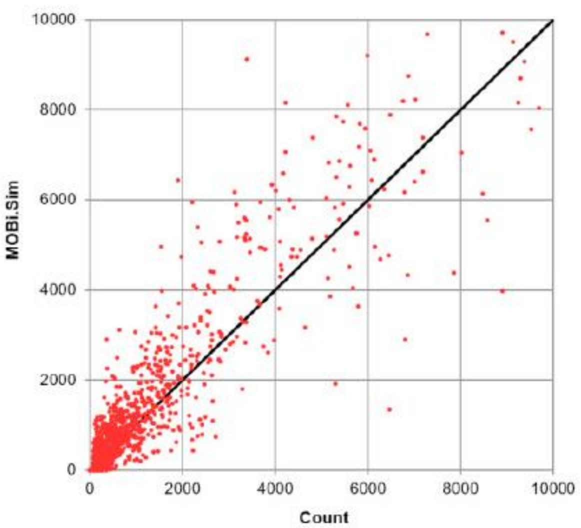

Figure 4. Validation of passenger volumes at rail stations (Scherr et al., 2020)

5 Expected Outcome

The expected outcomes of my PhD project will be the outcomes of the following schema: the optimal settings for the On-demand service, the modal split impact after implementing the service, and the economic balance sheet for every area where the On-demand transport is implemented. This can be achieved through the Cost Framework and Demand Model (Step1), the integrated Planning Optimization (Step 2) and the Validation (Step 3).

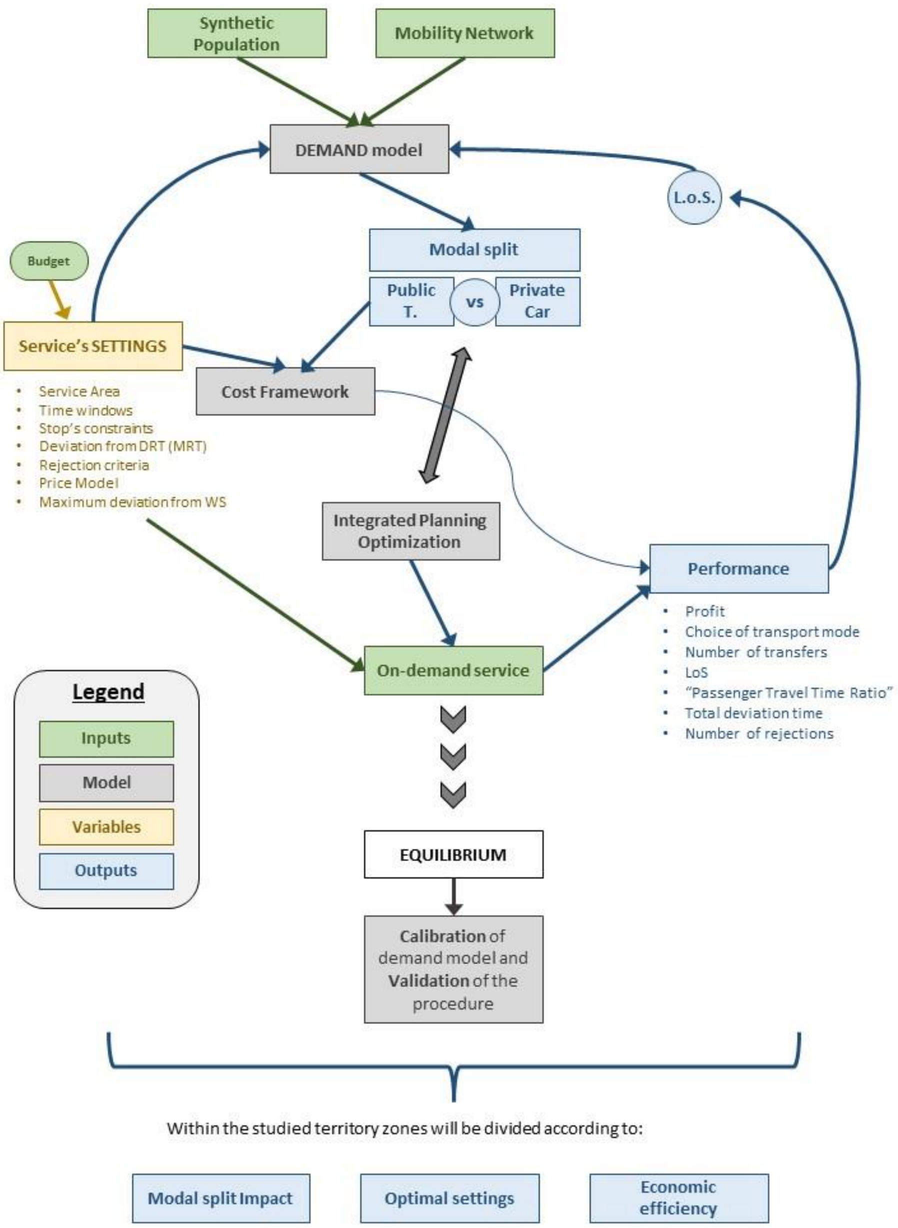

Figure 5. Global schema of my work

In a future step this procedure could also be translated in a Software that integrates all these blocks.

6 Conclusions

This 3-step quantitative method intends to be a substantial contribution to the transition of the transport network from a fragmented arrangement to a single system that encompasses all the potential of the offer in a joint effort, at the service of the citizen. This contribution does not neglect the economic side and the feasibility of this transition and, on the contrary, aims to provide strategic evaluation tools to operators, for the implementation of projects that go in the direction of M.a.a.S. in low density areas. The method is intended to promote interoperability between cantonal offices as purchasers and public transport companies as operators and to provide decision support in public transport service planning. This will significantly improve the coherence of planning and supply.

The creation of an integrated model (between on-demand buses and regular transit) that depends on the variables of which the designed service is to be composed, will be of enormous importance for future researchers and companies that want to experiment with new applications and simulations, on any type of territory. It will make it possible to better understand the connections between supply and demand in the intermodal transition between on-demand service and frequency-based transit. Thanks to these understandings, it will also be possible to configure the service in the best possible way.

My specific simulations (on Swiss territory) will then serve to validate the work done and to provide an order of ideas of the benefits.

A big challenge in MaaS is to find the junction point between public and private players' interests, and this research project gives a contribution in this direction of social utility. This step will make the alternatives to private transport more valid, making possible the desired shift from the modal split towards public transport.

Keywords

Agent-based modelling; M.a.a.S.; Transport Planning; Transport Integration; Modal Split; On-demand service; DRT; Dial-a-ride

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