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A Diachronic Agent-Based Framework to Model MaaS Programs

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Abstract: In recent years, mobility as a service (MaaS) has been thought as one of the opportunities for shifting towards shared travel solutions with respect to private transport modes, particularly owned cars. Although many MaaS aspects have been explored in the literature, there are still issues, such as platform implementations, travel solution generation, and the user's role for making an effective system, that require more research. This paper extends and improves a previous study carried out by the authors by providing more details and experiments. The paper proposes a diachronic network model for representing travel services available in a given MaaS platform by using an agent-based approach to simulate the interactions between travel operators and travelers. Particularly, the diachronic network model allows the consideration of both the spatial and temporal features of the available transport services, while the agent-based framework allows the representation of how shared services might be used and which effects, in terms of modal split, could be expected. The final aim is to provide insights for setting the architecture of an agent-based MaaS platform where transport operators would share their data for providing seamless travel opportunities to travelers. The results obtained for a simulated test case are promising. Particularly, there are interesting findings concerning the traffic congestion boundary values that would move users towards shared travel solutions.

Keywords: shared mobility; MaaS platform; diachronic network; shared transport data

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1. Introduction

Mobility-as-a-Service (MaaS) systems integrate different public and private transport services (such as buses, metros, trains, bicycles, rental vehicles, and ride-sharing services) into a single digital platform accessible via smartphones or other digital devices. Management and delivery of urban mobility services by MaaS systems would allow travelers to plan, book, and pay for trips through a centralized system [1–3].

Interest in MaaS programs stems from the opportunity they provide to create an inclusive transport system, which will contribute to social justice and environmental sustainability because it could promote the use of sustainable public transport by reducing dependence on the car, often a luxury for low-income people [4]. In principle, this leads to reduced emissions and helps to create more livable and less polluted cities by improving the quality of life for all citizens, particularly vulnerable communities that are often the most affected by pollution and congestion [5,6]. Reducing environmental impacts is also one of the key objectives of the city ecology concept, which aims to create better urban areas for people to live in by improving both industrial production [7] and the management of the transport system with increasing use of shared solutions and suitable pricing policies [8].

Concerning stakeholders, MaaS can play a significant role in helping companies to reach their target users and build brand awareness. This, in turn, might help improve their reputation and credibility in the marketplace. However, at the same time, service unreliability, inefficiencies (both in the provided transport service and the platform), and unfriendly apps or booking facilities might generate negative impacts on users, which would prevent the deployment of MaaSs while increasing distrust in shared/public transport services [2,9,10]. In summary, MaaS represents a step forward in the transformation of urban transport systems, putting the user at the center of mobility planning and management.

In the above perspective, the goal of this paper, which extends and improves a preliminary study carried out by the authors [11], is to test an agent-based diachronic MaaS simulator to understand the effects of shared travel opportunities on users. Particularly, the effectiveness of an MaaS program lies in its ability to shift users from private transportation modes, such as owned cars, to shared modes/services of transportation, such as buses, metros, and car/bike-sharing. In this context, the user's decision to change his/her travel behavior turns out to be crucial for the development of MaaS. Starting from the hypothesis, confirmed in the literature, that the car-owner user is unlikely to opt for shared travel solutions for commuting trips [12,13], this study aims to analyze under what conditions of congestion in the transportation system the private car user would be inclined to use MaaS solutions. User travel choices depend not only on socio-economic characteristics but also on the characteristics of the transportation supply system, particularly travel time and monetary costs. For shared transportation systems, the total travel time to accomplish a trip between a given origin/destination pair also includes the waiting time to use the service, a very important variable in transportation mode/service choices, and times associated with transferring between one mode/service and the next. In this perspective, in this work MaaS services offered in the platform were explicitly represented to account for waiting and transfer times by using diachronic networks, which allow transport services to be represented in a space-time context. In such a framework, the user can identify the travel solution that, at a given instant, provides the most favorable combination of transportation services for his/her trip.

To summarize, the paper intends to: (1) Set a diachronic agent-based framework to find MaaS solutions able to satisfy user's needs, based on factors such as travel times and monetary costs; (2) check under what traffic congestion conditions car-owning users would shift to shared solutions offered by MaaS systems. In these authors' knowledge, such issues have not been fully explored in the existing literature. Finally, insights provided by this approach could be used to design MaaS platforms able to provide suitable, effective bundles to users.

The paper is organized as follows. Section 2 discusses the most relevant literature dealing with the considered topics. Section 3 describes the main features of the proposed agent-based framework and the diachronic network model to simulate MaaS programs. Section 4 presents the obtained results, while Section 5 discusses the results and reports some main conclusions.

2. Related Work

Generally speaking, suitable MaaS implementations require long-established public transport systems and many shared modes available in the area, which would ensure a seamless and positive travel experience for users. Some of the MaaS pilots and schemes implemented all over the world provided some useful insights to identify both positive and negative aspects of this mobility opportunity, although such practical experiences are often case-specific and cannot be considered general enough for drawing wide-ranging conclusions [14–16].

A first issue concerns the exact MaaS features, which would allow comparing several experiences and drawing findings for setting suitable MaaS programs. Although there is a lot of research on the MaaS topic, a general consensus on what exactly has to be classified as "MaaS" and what its priorities are is still to be reached [17–19]. Some authors consider that mobility systems might be though as MaaS at different levels of integration and propose several integration levels—up to six. The "no integration level" is also considered, where each transportation service is offered independently by different stakeholders [20,21]. In this perspective, the integrated information about the travel opportunities in a given area, combined into multi-mode chains but without the need for payment or ticketing functions, might still be considered an example of MaaS programs. On the other side, some other authors consider MaaS simply as a digital platform that provides suitable, integrated information and support user travel plans. In the study by Athanasopoulou et al. (2022) [22], data concerning both transport demand and supply have been used to understand which factors are relevant for setting suitable MaaS platform, which provided planning, booking, and payment among the most relevant ones. One of the key factors influencing users' willingness to adopt MaaS programs is the provision of reliable, real-time, and flexible services [23]. This requires the integration of all available transport modes within the relevant area into the MaaS platform. Additionally, collaboration between stakeholders and strong backing from public authorities are crucial, as they significantly influence the development of appropriate business models [15].

One of the key challenges is designing MaaS bundles that meet the expectations of various user groups. MaaS bundle have been analyzed by Reck et al. (2021) [24], who provided an extensive review of the literature on MaaS bundle design. Among the main aspects, it emerges that few researchers have focused on the relation between city characteristics and bundle contents/levels [25], identifying a research gap in the effective design of MaaS bundles. Such gap depends also by the significant variation in the designs of choice experiments and the composition of the studied bundles. The main requirements and limitations of current MaaS schemes with respect to vulnerable groups and gender issues have been explored by Dadashzadeh et al. (2022) [26] and Aman and Smith-Colin (2022) [27], which highlighted some crucial aspects that should be carefully considered when developing MaaS platforms. Stated preferences (SP) data collection techniques [28] have been employed to study the relationships between users' preferences and socio-technical and psychological factors. The preliminary results of these studies show that psychological factors affect significantly user's preferences, together with socio-demographic factors—such as age, gender, household car-ownership, education, license, public transport pass—and travel characteristics—such as travel time and trip distance [29,30]. Tourist preferences have also been analyzed by using latent class choice model based on SP data, which showed the existence of not negligible heterogeneity among different tourist classes asking for customized MaaS bundles [31].

In the area of Sydney (Australia), an analysis has been made to study users' availability to subscribe to a MaaS bundle with respect to other already available travel opportunities [32]. An important issue that can deduced by these studies is the potential competition between existing transport services, whose technology is improving more and more in terms of payment facilities and online information, and MaaS programs, whose still unclear, in-progress features and niche product nature might reduce the real opportunity of implementing them. Although these studies suggested that MaaS could change travel behaviors for meeting sustainable goals, they also showed that MaaS commercial viability could be a real issue [18,33]. Implemented MaaS experiences have been analyzed by Arias-Molinares et al. (2023) [34]. The preliminary results of this comparison are that despite the variety of MaaS schemes implemented, most of them do not meet one or more of the key requirements that should distinguish a MaaS program and propose app-related programs rather than actual mobility packages. Based on similar considerations about the variety of MaaS schemes—or presented as such—a framework has been proposed trying to standardize the concept of an operational platform under a tendering authority control. More in detail, it considers the development of a competitive MaaS market through the use of a common access platform under the control of a tendering authority—which is also responsible for identifying a set of key performance indicators—so that a winning bid is selected in which multiple stakeholders ensure the implementation of multimodal services [35].

The above review suggests that simulating MaaS programs to understand how users are willing to change their car-owned choice towards shared travel solutions is a key factor for the successful implementation of MaaS systems [36]. In this perspective, agent-based models (ABMs) might be used to simulate the dynamic behavior of users and transportation fleets in an MaaS context. In fact, each agent has the ability to make autonomous decisions based on its own preferences, constraints, or goals and can learn from interactions with the environment and other agents [37–39]. These models enable the representation of complex scenarios in which mobility supply and demand evolve over time. For example, a first study addressed to model the complex dynamics and business models within MaaS scenarios [40] has been based on the use of SimMobility [41], an ABM developed as part of the Singapore-MIT Alliance for Research and Technology (SMART), which integrates various mobility-sensitive behavioral models and can simulate millions of agents representing all key transportation stakeholders. The literature about the use of ABMs in an MaaS context is rather poor, and few studies have tested ABM potentialities to investigate MaaS systems. A recent study has focused on identifying MaaS membership attributes [42]. The simulation environment incorporates an MaaS membership option, allowing agents to adopt a basic MaaS solution with a fixed daily subscription fee. Various scenarios have been simulated and evaluated, each defined by different subscription costs, to assess the impact of the MaaS membership pricing. The behavior of MaaS subscribers has also been explored, focusing on modal shift (before and after subscribing to the MaaS plan) and changes in total travel time. Another study, based on the ABM UrbanSim [43], has investigated population involvement in new transportation services to model mobility services in the city of Odawara, Japan [44]. Finally, in Nayeem et al. (2024) [45], an ABM-MaaS simulation model that includes three types of agents: MaaS fleet units, travelers, and a central intelligent mobility assignment module has been proposed. The model evaluates the processes of assigning mobility services while balancing competing interests, such as demand and supply, within the MaaS ecosystem.

In the context of ABMs applied to MaaS systems, this work proposes a new framework that mixes ABM approaches with supply service representation based on diachronic networks. The advantage of this approach relies on the opportunity to represent the space-time features of the transport services in order to find MaaS solutions available at the required time based on available data sets shared on the MaaS platform by the involved stakeholders. The simulation provides the different modal shifts for different scenarios at increasing levels of traffic congestion, which made it possible to identify the congestion range above which users prefer to use shared modes/services instead of their own cars.

3. Materials and Methods

The proposed framework focuses on the identification of suitable bundles based on mono- or multi-mode services provided by one or more transport operators. The preliminary hypothesis is that an MaaS platform is available where data among travel operators are shared and searches of bundles may happen depending on users' requests. In addition, it is assumed that business and technical requirements are fulfilled (e.g., booking, ticket, and payment services); therefore, it is possible to provide integrated mobility services able to ensure seamless travel experiences to users.

To examine the effects of MaaS bundles on user travel choices, the following steps have been applied (Figure 1). The first step has been to set the diachronic networks for representing travel services offered by the travel operators on the platform. Then, the agent model has been defined, depending on both the user's features and the diachronic network supply representation. Finally, the two steps have been combined to analyze the effects of MaaS bundles on users' choices, particularly those concerning the choice of owned cars. The novelty of this approach relies on the combination of the diachronic network approach with agent-based models to provide travel solutions that depend on the interaction between existing transport supply and the user's request.

The following sub-sections describe the applied models (i.e., diachronic networks, ABMs) and their specification in the proposed framework for identifying both suitable bundles and their effects in modifying the initial users' choices, particularly car-owners' ones. Furthermore, a brief introduction, preparatory to the proposed framework, is also provided about the basic concepts underlying the modeling of transport systems.

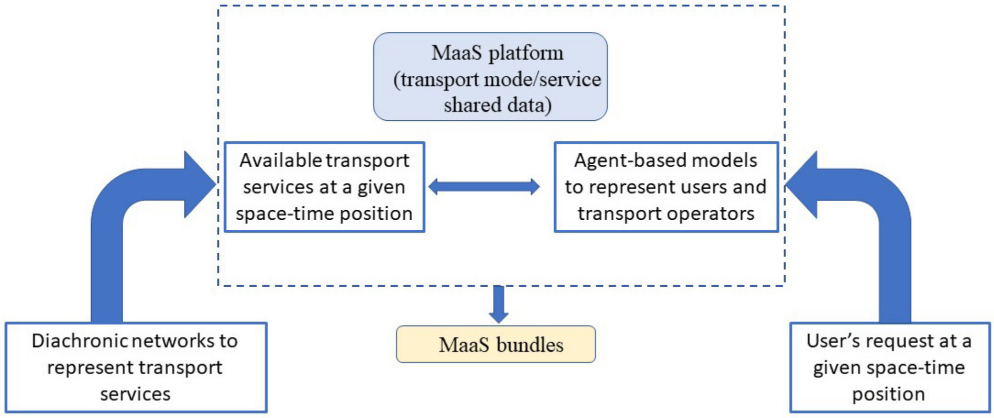

Figure 1. Overview of the methodological approach.

3.1. Transport System Modeling: Brief Overview

Users, representing the transportation demand, move between origin/destination points in a given area in order to benefit from opportunities offered at the destination point and not available at the origin point. To this aim, they use the available transport supply, which is a set of infrastructures and services making it possible to perform trips between origin/destination points (see for example [46] for an overview). Users make choices related to their trips, such as departure time, transport mode/service, and path in the given transport system. Most literature dealing with user travel choice relies on discrete choice models to estimate the choice probability associated with each available alternative. The hypothesis of "rationality" is the basis for the widely used random utility discrete choice models [47].

As for the used mode/service in urban environments, the main supply characteristics that affect a user's decision to use it are travel time and monetary costs [46]. Additional features that may influence the user's decision are also comfort, safety, and availability in space and time. When several modes/services are used to move between an origin/destination pair, users are particularly affected by transfer times and monetary costs linked to multiple tickets. In an MaaS perspective, using multiple services provided by some transport operators requires organizing the several legs in order to minimize transfer times and monetary costs due to possible multiple tickets. However, different users have different expectations and different preferences; therefore, a (personalized) MaaS bundle should provide an optimal service combination by considering such aspects.

3.2. Diachronic Network Models

The diachronic network (DN) model is a graph-based representation of activities carried out in different space and time positions. With respect to traditional graphs that represent the spatial structure of the network, the main feature of a DN is the inclusion of time as an explicit dimension. This allows changes in infrastructure and shared services to be modeled over multiple periods, including changes in transportation routes or lines (mainly for scheduled services that are different in time and may have different features in different time periods) as well as changes in the frequency of services (depending on the demand distribution over time).

DN models may be used to represent shared transport systems [48]. The main feature of such systems is that they offer discontinuous services both in space and in time. In fact, services are available only at discrete points in spaces and at discrete times. For example, scheduled services (buses, trains, metro) can only be used between terminals (stops, stations) and are only available at certain time instants (the departure times of the runs). Similarly, station-based shared systems (like bike or car sharing systems) are available only at a given space (the station) and at a given time (depending on the availability of the car in the case of booking systems or the availability of the bike due to their limited number). The transport supply models representing such systems are therefore different from the transport supply models used for representing road networks, which are instead continuous and simultaneous systems where cars may operate at any space and time.

In a DN model, each node has an explicit time coordinate and represents an event that occurs at a given instant. Figure 2 shows an example of DN applied to shared transport services. In the figure, each temporal centroid represents the transportation demand at a given time, while along the stop axis, each node represents the space-time position of the service. As an example, the space position corresponds to the physical stop location, while the time position corresponds to the time the service is available at the stop—e.g., a bus is stopping. Links correspond to the space-time relationship between two nodes, such as travel time to reach the stop or travel time for reaching the parking lot for car-sharing station-based services. Links from the departure stop to the arrival stop represent single runs, which have a space-time representation.

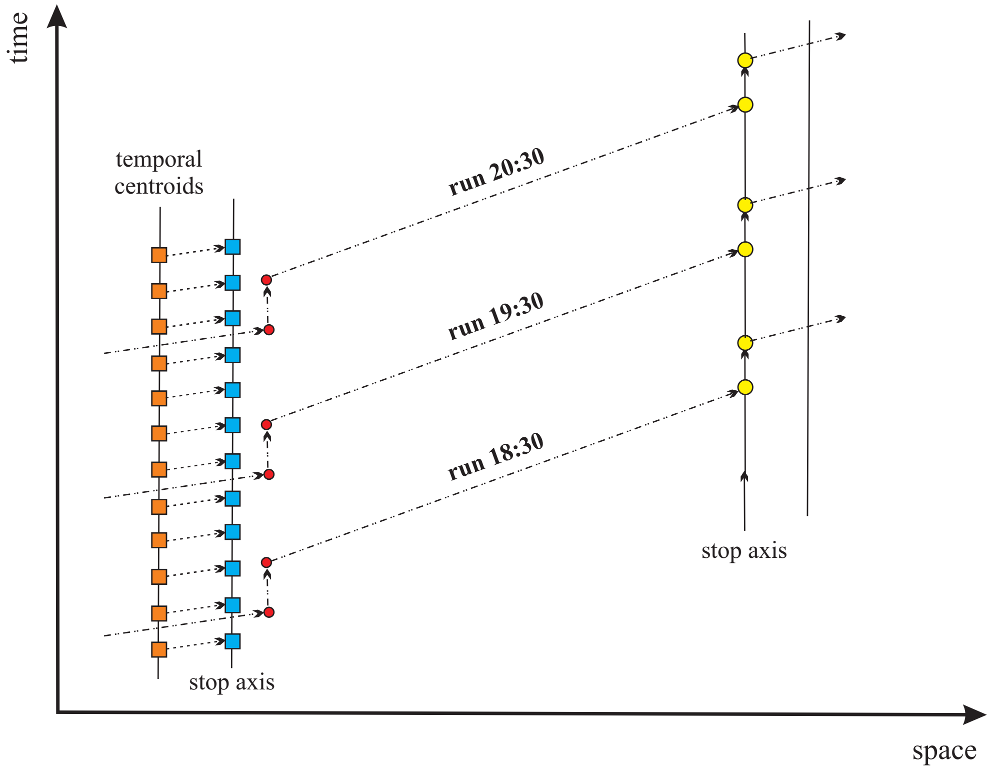

Figure 2. Diachronic network: representation of transport supply for scheduled services.

3.3. Agent-Based Models (ABMs)

Very shortly, ABMs are simulation tools that represent complex systems by using autonomous agents, defined as individual entities with specific behavioral rules [49]. ABMs allow for detailed representations of agents and their interactions. This makes it possible to model realistic behaviors and account for elements of heterogeneity, adaptation, and learning.

Among the several features of an ABM, the core elements for the purposes of this study are listed below:

- The agent:
  - Each agent represents an autonomous entity with a set of properties (such as resources and preferences, which can change over time) and rules (such as decisions based on local information, interactions with other agents or the environment, learning, or adaptive mechanisms) that determine its behavior. Agents can be very different from each other (heterogeneous agents) or homogeneous (identical agents).

- The environment:
  - The environment is the space within which agents exist and interact. Such space can be: (1) physical (e.g., grid or geographic map) or conceptual (e.g., economic marketplace or social network); (2) dynamic, if it changes over time in response to the actions of agents, or vice versa static. Furthermore, agents can change the environment (e.g., by consuming resources), and the environment can influence agents (e.g., changes in available resources influence their behavior).
- The Agency:
  - The agency gives agents the ability to act autonomously, make decisions, adapt, interact with the environment and other agents, and influence the evolution of the simulated system. In summary, the agency allows agents to have an active role in the simulation process by exploring the complex relationships arising from the interaction of multiple autonomous entities.

3.4. Methodology

Simulating the complex relationships occurring in an MaaS system requires modeling both transport demand (i.e., user's requests) and transport supply (i.e., the offered services) with the aim to provide travel solutions coherent with user's mobility needs and the existing transport services.

The proposed framework uses ABMs to find suitable travel solutions depending on users' requests and available services. In detail, two types of agents are considered: the users, who are characterized by a set of features representing their travel preferences, and the transport operators, whose features are represented by the diachronic networks related to the services they offer. Both are acting on the MaaS platform and are supported by the agency, which provides directory and communication services.

In detail, each user is represented by his/her personal agent (PA), while each transport operator is associated with its agent (PO). From a transportation system perspective, PAs represent transportation demand and POs represent the offered transportation supply. The agency is interfaced with both PAs and POs; in other words, it acts as a liaison between them (Figure 3).

Each PA associated with his/her user i is described by a set $(x_1^i, x_2^i, \cdots, x_m^i)$ of factors representing the user's characteristics and preferences:

$$PA^i = PA(x_1^i, x_2^i, \cdots, x_m^i) \quad (1)$$

The agency receives the information contained in PA^i and, depending on the associated travel user's request, interfaces with the POs to find suitable bundles (see the next paragraph), which in turn are offered to PA^i. This latter selects the bundle, among those provided by the agency, that fits better his/her user's preferences based on criteria deriving from $(x_1^i, x_2^i, \cdots, x_m^i)$. Generally speaking, the most relevant criteria to select alternatives are minimum travel time, minimum monetary costs, combination of minimum travel time, monetary costs, and other factors such as comfort, safety, and so on (also defined as "generalized travel cost"). In summary, PA^i provides his/her user with personalized recommendations by interacting with all the POs associated with the transport operators through the agency. Finally, each user i will perform all the necessary payments in an automatic way through the associated PA^i. This also includes the pay-for-use modality (i.e., like the car-sharing case).

To identify bundles, the supply representation is required. The transport services offered by the given PO at the time t of the user's request are represented by a diachronic network $DN^{PO}(t)$ because they are available at given space-time positions in the considered area. Particularly, if the service is provided at any physical point in the area, like in the case of free-floating car-sharing services, links represent potential constraints for the service. In other words, if at the time of the user's request a car-sharing service is available at another space-time point, the user has to wait at the same location or move to another point to get the service. In both cases, links connect two space-time positions.

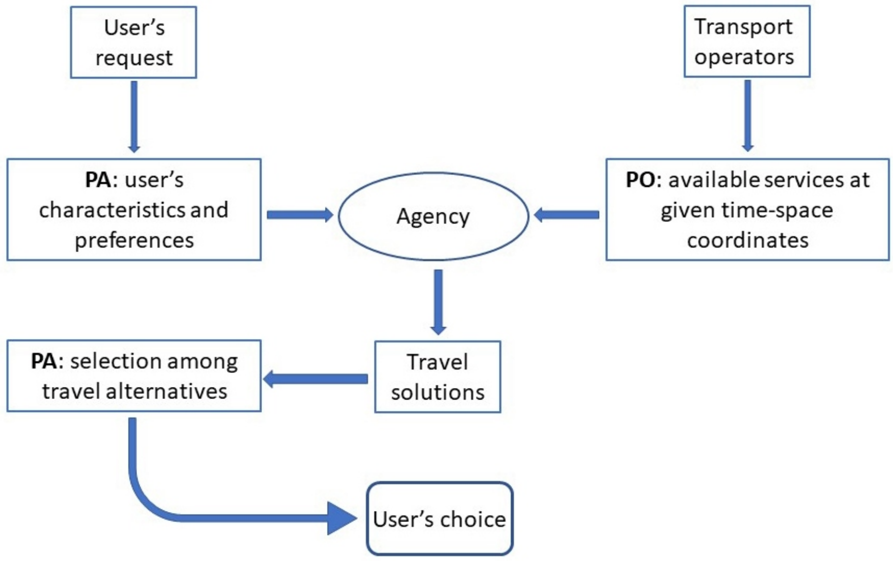

Figure 3. The agent-based structure including user's choice by discrete choice models.

A multi-layer representation has been adopted to simulate the transport services in the area. In fact, given that multiple *PO*s would operate on the same MaaS platform, each offered service is assigned to a given layer numbered from 1 to n that contains the diachronic network of the associated services ($DN_j^{PO}(t), j = 1, \cdots, n$) as depicted in Figure 4.

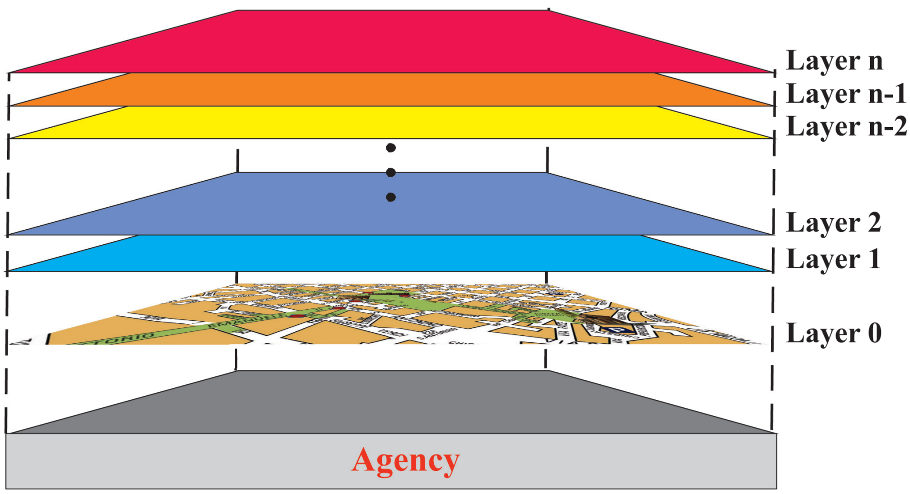

Figure 4. Multi-layers structure in the proposed framework.

Note that layer 0 is associated with the urban map of the considered area. The current position of the user is identified in this layer by suitable location devices (e.g., mobile phone GPS) and represents the origin of the trip. Physical nodes allowing access to the services in layers $1, \cdots, n$ are considered available to users if they are within a radius of 500 mt around the user's location at layer 0, which is considered a limit distance the user is willing to walk to get a service. In addition, (vertical) connections among layers are also considered, which allows the combination of travel services belonging to one or more layers (i.e., *PO*s). This representation allows considering multi-mode/services depending on their effective availability at a given space-time point. To link the desired origin/destination pair requested by the user, a path has to be identified in the multi-layer diachronic structure, which is a sequence of links belonging to one or more layers, i.e., mono or multi-mode/service options. In the case of multi-mode/service options, the path also contains vertical links connecting two layers.

In summary, the following operational steps are performed to select the best bundles based on the user's preferences and the available services at the time of the request:

1. At time t, user i sends the trip request to his/her PA^i, which contains data related to i. Based on the request, PA^i asks the agency for information and sends detail on the user's position;
2. the agency interacts with all the POs and selects a multi-layer sub-network from the DNs represented in the several layers. The selection of the sub-network is required because only services starting at the time t of the request, or within a suitable range $t + \Delta t$, are considered;
3. the agency selects multi-layer paths (defined as sequences of links belonging to one or more diachronic networks) in the multi-layer sub-network based on the minimum generalized cost, or a unique component such as travel time or monetary cost, depending on $(x_1^i, x_2^i, \cdots, x_m^i)$. To obtain suitable paths, their selection also meets: (i) topological criteria (each link belonging to the path leaves the origin node/approaches the destination node); (ii) behavioral criteria (unrealistic paths, such as the ones bouncing repetitively among layers, are not considered); (iii) distinctive (paths should overlap for less than a given percentage).
4. The agency computes the first k paths with the lowest generalized costs instead of a unique path for linking the desired origin/destination pair in order to consider all the information contained in PA^i;
5. The agency sends the paths, i.e., the travel solutions, to PA^i, which will rank them based on the user's stored features $(x_1^i, x_2^i, \cdots, x_m^i)$;
6. Finally, PA^i suggests one or more solutions meeting the features of i and uses the information concerning his/her effective choice to update his/her profile.

It is worthwhile to note that the core of the proposed approach is the selection of the best options based on the user's preferences and the available services at the time of the request. Travel options are selected based on the "advantages" and "disadvantages" of each provided alternative, where such advantages and disadvantages depend on the user's preferences and features together with transport supply characteristics. In other words, the selection of the best options is coherent with the user's behaviors as modeled in discrete choice models. Note that in real life the user's strategy will always try to optimize choices to satisfy his/her preferences, but the final choice will depend tightly on the information available in the decision-making process.

Finally, this study focuses on checking the effects of MaaS personalized bundles—as identified by the agency and then selected by the PA—in discouraging the use of individually owned cars. Therefore, after applying the ABM framework to identify personalized bundles, discrete choice models have also been applied to compute the probability that the user will choose the bundle selected by the PA, thus changing his/her car-owned transport mode towards an MaaS solution. In the considered context, a simple multinomial logit (MNL) model has been considered [50], whose general expression is

$$p(b) = \frac{e^{V_b}}{\sum_h e^{V_h}}. \tag{2}$$

where $V(.)$ depends on the characteristics of the considered alternative (e.g., private car, car-sharing, bus, and so on); the sum refers to all the available alternatives in the choice set.

4. Results

In this section, an experimental study has been conducted to test the proposed ABM-DN framework in a MaaS context, which extends and improves the preliminary study conducted by the authors [11].

A simulated urban environment, which represents the transportation network of a medium-sized city, has been considered. In the following, after setting the main aspects of the test case, the results are presented.

Given the simulation nature of the experiment, the first step is to prepare the simulated users' features and preferences and store them in the profile managed by his/her *PA*. In a real case, this information comes from initial inputs and further updates that derive from monitoring the effective user's choices by his/her *PA*. In this simulation, such information has been obtained by generating randomly $(x_1^i, x_2^i, \cdots, x_m^i)$, which include both socio-economic features (such as income, age, and so on) and travel preferences (such as trip origin/destination, departure time, comfort expectations, and so on). Previously available data referred to users' choices in urban contexts have been used to this aim [51]. To check the effectiveness of MaaS bundles in discouraging the use of privately owned cars, only users supposed to have their own cars have been simulated. In this perspective, they can only reconfirm their own car as a transport mode or choose the MaaS solutions provided by their *PA* based on the set of options found by the agency.

As for the simulated urban context, the road network is represented by square grids, whose side is 80 mt long. This value is consistent with real average urban distances between two intersections in medium-sized urban areas in EU. Two-way roads with the same capacity have been assumed, which does not lose generality for the purpose of the experiment. Furthermore, travel times are associated with each road in the network, based on some known cost functions for congested transportation networks (see for example [46]. This structure is reported at layer 0 and represents the base network allowing private car journeys between origin/destination pairs.

The ABM simulator applied to this study is the adapted version of the simulator previously developed by the authors [52–54] and already tested in an MaaS context [11]. In the simulator, the agency and the agents employ a message-based system, where each message contains the following information: (i) sender, (ii) receiver, (iii) content type (e.g., trip, information, action), and (iv) content details (e.g., route, preferences, etc.).

In the simulation, car-sharing, bike-sharing, subways, and buses have been considered available in the MaaS platform. The related features are represented in the diachronic networks associated with their corresponding *PO* at the assigned layer. Table 1 reports the main characteristics of the considered services.

Without loss of generality, the vehicles associated with the simulated transportation modes have been considered homogeneous. This is a realistic hypothesis because it is expected that the available services are provided with standardized features for all the considered modes.

Physical stations and stops for the considered modes have been randomly located at layer 0 at the prefixed average distances (see Table 1). The diachronic networks at the layers (3–4) have been obtained by generating some lines connecting the stations/stops previously located at layer 0 by considering that the average running time between two terminals must fit the values in Table 1. Scheduled services have also been generated by splitting the simulation period into sub-intervals and setting departures at the terminals coherent with the frequency in Table 1, which considers variations during the simulation period. As for layers (1–2), the nodes in the diachronic networks correspond to the space-time position of cars/bikes at their respective stations, while links are set as described in Section 3.4. The time feature of nodes has been generated randomly in order to simulate the probability of finding an available car/bike at the time of the request. As for parking cost, it has been assumed that car-sharing allows for parking without paying, while private cars have been subjected to parking fees. In the simulation, such cost has been assumed constant and equal to 3 euros to consider an average parking time of less than 2 h.

Finally, in the simulated environment, users' requests have been generated at random space-time positions at layer 0, which reproduces the user (origin) location obtained by GPS (or similar) devices and trips between exact origin/destination pairs.

Table 1. Transport mode features in the experimental context [1,2].

Main Features	Car-Sharing (Layer 1)	Bike-Sharing (Layer 2)	Subway (Layer 3)	Bus (Layer 4)
Accessibility	Station based	Station based	Stations	Stops
Commercial speed	–	–	40 Km/h	15 Km/h
Maximum running time between two terminals	–	–	45 min	45 min
Minimum running time between two terminals	–	–	25 min	25 min
Average distance between stations/stops	500 mt	300 mt	500 mt	300 mt
Frequency range	–	–	3–5 min	7–10 min
Parking cost	0	0	–	–

[1] Commercial speed includes running time and accessory times due to deceleration/acceleration at stops, waiting time for passenger boarding/alighting to/from the bus, and effects of road congestion. [2] For car-sharing and bike-sharing, speed has been estimated by using empirical equations [46].

To find MaaS solutions, i.e., multi-layer paths, a variant of the Alpha-Beta Pruning algorithm [55] has been used by the agency, guided by suitable heuristics to improve the cut-off strategy. Criteria considered in the algorithm are travel time, monetary cost, comfort, and safety, these latter measured in a suitable scale $[1, \cdots, 5]$ and based on the already cited data in [11,51]. Additional features have also been considered:

- waiting times at the transfer points have been associated with links between layers (i.e., transport modes);
- a vertical link connects two layers if a service is available at the time t of the trip request.
- the algorithm search horizon has been set to $h = 3$, i.e., only two modes/services are allowed; such condition considers that the disutility associated with more than two mode/service changes prevents users from considering this option as a possible solution;
- if walking is required between two nodes in the same layer and the distance is less than 500 mt, the related travel time is automatically added to the current path cost; such a condition considers that users are willing to walk between two nodes, i.e., stops or stations, if distances are less than 500 mt;
- connections between different transport services have been considered reasonable if the connection time is less than 15 min; connection time includes the pedestrian time to reach the station/stop and/or waiting time for the transportation service to be accessible;
- private car paths have also been found at layer 0 based on link travel times in order to compare them with the alternative solutions provided by the agency.

Four alternative scenarios have been simulated by increasing free-flow link travel times with step +15% to consider different congestion levels. It is worthwhile to note that this increase affects both private cars and car-sharing while having no effects or limited effects on bike-sharing, buses, and metro because of their features. The simulations for the several scenarios refer to a three-hour time interval, with 10,000 simulated private car users and trip requests for the different destinations randomly generated. If the distance between the origin/destination pair is less than 500 mt, this simulated trip has not been considered.

For each simulated user i, the probability that he/she would choose one of the travel solutions provided by the agency has been obtained by Equation (2), where $V(.)$ includes both the user's features as stored in PA_i and the relevant characteristics (i.e., time, monetary cost, and so on) of the considered alternatives [46,47], which are multi-layer paths in the simulated environment. Table 2 summarizes the results. Figure 5 depicts the percentage variations of users' choices in the four simulated scenarios; particularly, scenario 1, corresponding to free flow conditions, has been considered as a baseline, and changes in the user's choices in scenarios 2, 3, and 4 have been computed with respect to scenario 1.

Table 2. MaaS bundle choice percentages in the simulated scenarios [1].

	(Scenario 1) Free Flow Conditions	(Scenario 2) (+15%)	(Scenario 3) (+30%)	(Scenario 4) (+45%)
Private car	(95%)	(92%)	(84%)	(79%)
MaaS alternatives (total)	(5%)	(8%)	(16%)	(21%)
Car-sharing alone	(3%)	(3%)	(4%)	(6%)
Bike-sharing alone	(2%)	(5%)	(5%)	(5%)
Car-sharing + bus	–	–	–	–
Car-sharing + metro	–	–	–	–
Bike-sharing + bus	–	–	(1%)	(2%)
Bike-sharing + metro	–	–	(6%)	–
Bus + metro	–	–	–	(8%)

[1] Percentages have been approximated to integer values. Note that this implies that low values close to zero are neglected.

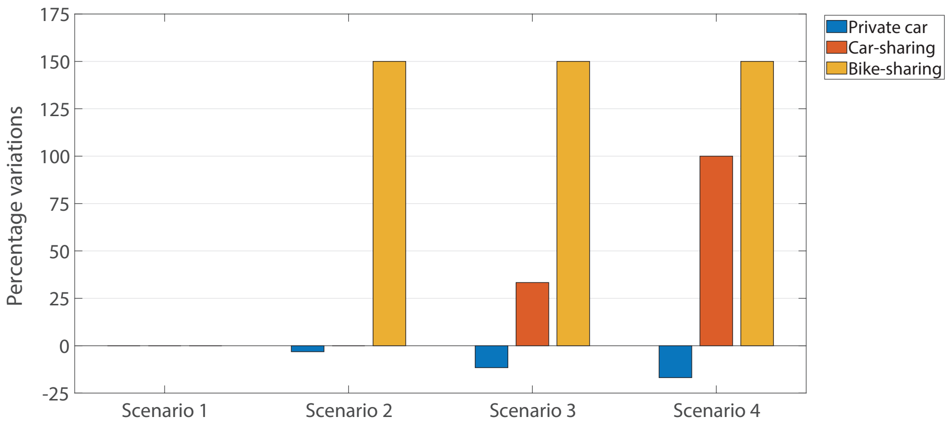

Figure 5. Percentage variations of users' choices in the simulated MaaS context.

5. Discussion and Conclusions

The results obtained by using the ABM-DN framework depend on the considered supply system, the generated demand, and the assumed values of all the relevant variables, which in any case correspond to realistic assumptions and values. Therefore, it is worthwhile to note that, although based on a simulated environment, for a given real system meeting the established conditions, there are some interesting findings that might support the development of suitable MaaS systems. In the following, first the four simulated scenarios are discussed separately, and therefore some general conclusions are presented.

In scenario 1, which corresponds to free-flow road traffic conditions, a low percentage of car owner users change private cars towards car/bike sharing solutions, and no users are willing to use public transport like buses or metros. These results are slightly different from the preliminary ones in [11], which provided 0 changes with respect to the use of private cars. The main difference is that in this study users are generated at a specific time-space point, which is coherent with real situations; therefore, there is easier access to shared services. The previous study [11] considered an aggregate representation of users that is supposed to be located in the so-called demand centroids [46].

In scenario 2, where link travel times for private cars are increased by 15% with respect to scenario 1, the choice percentages are not very different from the previous results. In fact, a slight decrease is observed in the use of private cars, while car-sharing is almost the same. On the other hand, bike-sharing shows a slight increase with respect to scenario 1, which would depend on both the easier accessibility to bike-sharing stations—as discussed before—and the capability of bikes to move easier in more congested roads. Again, metro and bus percentages are negligible.

In scenario 3, where link travel times for private cars are increased by 30% with respect to scenario 1, changes are more significant. Private cars reduce more significantly, while combined solutions (metro/bus + bike-sharing) appear. Again, the increased congestion reduces the advantages of private cars, but car-sharing is less attractive than bike-sharing. In fact, although car-sharing benefits from free parking, it suffers from congestion effects similarly to private cars.

In scenario 4, finally, congestion effects are more relevant because link travel times for private cars are increased by 45% with respect to scenario 1. Results show significant reduction in private car percentages and a sudden increase in combined bus + metro solutions. Apparently and surprisingly, car-sharing increases with respect to the previous scenario and seems slightly more attractive than the bike-sharing solution. Furthermore, bike-sharing + metro drops drastically while bike sharing + bus increases slightly with respect to scenario 3. It is reasonable to expect that increasing congestion would reduce the use of cars, both private and shared; however, in this case, it seems that the increased travel time is partially compensated by the car comfort and the free parking cost, which induce users to still prefer car solutions even if shared.

There are two main aspects to be discussed: (1) the effectiveness of the proposed framework based on the use of both ABMs and DNs; (2) the effects of MaaS personalized solutions for supporting changes in the use of private cars.

As for the framework, the simulations have provided realistic results and have showed the potentialities of the ABM-DN approach for exploring MaaS bundles that could modify user's choices. Particularly, DNs allow offering personalized solutions meeting user's request effectively.

As for the results of the simulation to test user's propensity to shift from private car to shared solutions, some interesting insights have emerged. Generally speaking, users tend to confirm the use of their owned car for medium-low congestion levels, but as congestion increases they are more willing to change transport mode. Particularly, as personalized space-time solutions are offered at the time of the request, users are willing to shift to car-sharing solutions also in the case of free-flow conditions—which represent the baseline scenario—while they tend to appreciate public transport combinations for high congestion levels. Bike-sharing solutions show almost constant percentages as congestion levels increase. In other words, in this study, it emerges that car owners are only slightly willing to shift from car to bike, while they could choose public transport more than bikes for high congestion levels. This result depends on a combination of factors that includes not only supply features but also socio-economic characteristics of the users stored in each *PA* in the proposed ABM-DN approach. Although coming from a simulation, these results show realistic findings as they capture users' inelasticity to leave their owned car for other travel solutions.

Finally, as reported in Table 2, the percentage of MaaS solutions tends to increase, particularly from 5% in scenario 1 to 21% in scenario 4, as congestion levels increase. This result could support the hypothesis that MaaS solutions might be effective in highly congested system, provided that personalized space-time solutions are provided.

Although the results obtained are encouraging, further developments are expected. First, free-floating systems could increase car/bike-sharing use and should be properly simulated. Second, additional data coming from real contexts could help improve the ABM-DN simulator and better support the exploration of MaaS bundles. Third, stated preferences data suitably collected could help improving the ABM-DN simulator, again for finding effective bundles. Finally, further research is expected to estimate the changes in travel cost as a consequence of changes in users' choices.

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