An Agent-based Framework including Diachronic MaaS Represention

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Abstract
Mobility as a Service (MaaS) opportunities have received great attention both in the literature and in practical implementations, as well as projects and specific case studies. Even though the well-known expected potentialities, however there are still issues to be solved, which range from platform implementations to user's role for making effective the system. From the user side perspective, particularly important are those aspects as reliability and effectiveness of many available travel services, often managed by a unique platform. In other words, how much in MaaS schemes the offered combination of transport modes promising a "seamless and efficient experience" – included connection times and fares – potentially is able to meet users' expectations. Starting from the above perspective, this paper proposes an agent-based framework to simulate MaaS programs by using diachronic representations of the transport services offered by the different stakeholders that share the MaaS platform. In particular, the attractiveness of some MaaS programs have been compared to the one of private cars for the same trip, from a user's perspective, in a simulated agent-based urban scenario. The obtained results, although simulated in this preliminary test, show that the proposed framework would both provide suitable mobility solutions by using the potentialities of the diachronic network approach and capture user's preferences. Particularly, the user propensity to change private cars towards shared solutions increases as congestion in private car network increases.

Keywords
Diachronic network, MaaS, Public transport data, Shared mobility, Shared platform

1. Introduction

Mobility as a Service (MaaS) might be defined as a mobility model assuming a shift from a paradigm of personal ownership of individual transportation modes to the one of shared mobility services. The key factors of a MaaS are interoperability, data sharing and inclusion [1]. The goal of such systems is to make available a set or interoperable transport services in order to provide seamless, safe, efficient and fast mobility services [2]. To this aim, the ability of transport operators to integrate available public and private mobility services is crucial to enable users to satisfy their individual mobility needs in a simple, accessible, flexible and personalized way [3, 4].

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An important element of a MaaS systems is the integration of many transportation modes into a single technological platform accessible via smartphones or other digital devices. The platform is the core element of the system, which allows combining different mobility options, both in terms of journey planning – such as intermodal route planner, real-time information on travel times and distances [5] – and in terms of use – such as reservation and payment of services [6]. The design and development of MaaS platforms requires collaboration among transport service providers, software developers, regulators in order to ensure effective interoperability and a smooth customer experience.

From the customer's side, a MaaS system offers the opportunity to plan point-to-point trips through the digital platform, by taking advantage of several transport systems available in the area and possibly by using a single or season ticket [7].

All over the world, there are examples of MaaS implementation, such as in Finland (Helsinki, "Whim"[1]), France (Paris, "Navigo"[2]), Germany (Berlin, "Jelbi"[3]), Japan (Tokyo, "JapanTaxi"[4] and "Tokyo Subway Navigation"[5]), Singapore ("Beeline"[6]), Sweden (Stockholm, "Sthlm Traveling"[7]), The Netherlands (Amsterdam, "Gaiyo"[8]), UK (London, "One Account" [9]). Most of such systems are based on the use of an app, which allows users to access various transport services; find alternative transport routes; plan, book and pay for various transport modes [8, 9].

Some of the advantages of MaaS systems for improving urban mobility are efficiency, sustainability, and monetary costs, which correspond to optimize the use of existing transport resources together with the use of public and shared electric-powered transportation modes to foster a more sustainable environment [10] at reduced monetary costs. In fact, using MaaSs would be cheaper than buying, maintaining and operating a private vehicle [11]. Furthermore, MaaS could encourage the development and adoption of digital technologies and innovation – such as artificial intelligence and the Internet of Things (IoT), which would improve both efficiency and user experience – leading to smarter and integrated mobility solutions [12].

Although there are many positive effects, however some points against MaaS systems are financial sustainability [6], integration of services, digital exclusion, effects on public transport [13]. Particularly, service integration requires integrating different transport operators and services into a single platform. This might be a critical step in MaaS implementation, due to differences in technology, regulation and commercial interests of the involved stakeholders [14].

Similarly, potential digital exclusion is another crucial factor, because not all users have access to smartphones or are comfortable when using apps, which may limit the accessibility to MaaS opportunities [15].

Underlying MaaS is the ability of the system to have an exact representation of the transport services over time, and this can be achieved by using diachronic networks. This term combines the concepts of "network", which refers to a structure of interconnected nodes, and "diachronic",

[1]Whim, https://whimapp.com, 2024.
[2]Navigo, https://www.ratp.fr/en/titres-et-tarifs/navigo-liberte, 2024.
[3]Jelbi, https://www.jelbi.de, 2024.
[4]JapanTaxi, https://go.goinc.jp, 2024.
[5]Tokyo Subway Navigation, https://www.tokyometro.jp/lang_tcn/news/188521.html, 2024.
[6]Beeline, https://www.beeline.sg, 2024.
[7]Sthlm Traveling, https://sthlmtraveling.se, 2024.
[8]Gaiyo, https://gaiyo.com, 2024.
[9]One Account, https://www.oneaccount.com/onev3/service/home/service-landing.html, 2024.

which refers to the temporal or historical dimension.In detail, a diachronic network is a type of complex network used to analyze and visualize the temporal sequences of events or identify relationships, recurring patterns and trends by allowing analysts to explore significant changes over time [16].

A diachronic network highlights the relationships and dynamics that unfold over time, allowing observers to see how connections between nodes evolve and change over time. Nodes represent events, elements, or actors within the system under study, while edges represent the relationships or interactions between them. Edges can be directed or undirected, depending on the type of relationship they represent.

Starting from the above overview, the goal of this paper is to design an agent-based diachronic MaaS simulator to identify single or multimodal services provided by one or more transport operators, which would be proposed as a single mobility service to users accordingly to the MaaS purposes. The core aspect of the simulator is the adoption of a diachronic network model for representing travel services, so that users can find the most convenient travel combination at the given time, with respect to the opportunities that arise at that time interval. Particularly, the information provided to the user could be optimized with respect to different criteria such as, for example, travel time, monetary cost, comfort, safety [17]. By setting a simulated urban scenario, some experiments have been conducted to test whether the proposed agent-based diachronic MaaS scheme might satisfy users' expectation. More in detail, since MaaS scheme implementation should meet the general goal of shifting current individual car users towards shared transportation modes, the experiments have been addressed to check user's propensity to change his/her owned-car trip choice to the benefit of MaaS shared solutions.

The results obtained showed that users would change their private car mode as the congestion of the private car network increases. In this case, preferred MaaS solutions are the ones with public transport mode options, particularly metro solutions which do not suffer from congestion effects.

The rest of the paper is organized as follows. Section 2 presents an overview of the most relevant literature with respect to the considered topic. Section 3 describes the proposed agent-based framework while Section 4 deals with the designed MaaS simulator. In Section 5 the simulations carried out and the obtained results are presented and discussed. Finally, in Section 6 some main conclusions are drawn.

2. Related Work

Many studies in the literature have explored the potential of MaaS programs for developing suitable MaaS bundles to be offered to users. Most of these studies have focused on user's and stakeholder's expectations for understanding the main features of MaaS schemes.

The Sydney MaaS trial [18] has been set to study user's availability to subscribe a MaaS bundle with respect to other already available travel opportunities. Although these studies suggested that MaaS could change travel behavior for meeting sustainable goals, however, they also showed that MaaS commercial viability could be a real issue [11, 19]. Many SP-based MaaS studies have been conducted to analyze the relationships between users' preferences and socio-technical factors together with psychological factors, the results being that, although there is still research to be done, a not negligible influence has been proved in most studies for the psychological factors affecting user preferences, while similar results about the significance of socio-demographic factors – such as age, gender, education, household car-ownership, public transport pass and license – and travel characteristics – such as trip distance and travel time – have been obtained in many studies [20, 21].

The exact MaaS features is also another important issue. Some authors consider MaaS simply as a digital platform that provides suitable, integrated information and support user's travel plans. MaaS platform features have been explored by Athanasopoulou et al. (2022) [22], based on data concerning both supply and demand sides, and the study showed that planning, booking and payment are among the most relevant factors for MaaS platforms together with finding suitable MaaS bundle designs to match the expectations of several user groups. Among the factors that affect user's propensity to use MaaS programs, providing accurate, real-time and flexible services is one of the most important [23], which implies the integration of all available modes in the considered area into the MaaS platform. This also requires cooperation among stakeholders as well as strong support by public bodies, which has also important impacts on the formulation of suitable business models [24].

Existing real cases have been analyzed by Arias-Molinares et al. (2023) [25], by concluding that although there are many implemented schemes proposed as "MaaS", however most of them do not satisfy some of the requirements that could be considered key features of an actual MaaS and such implemented systems propose mainly app-related functions than 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.

In this context, descriptive or predictive computer simulations may be used for the analysis of strategies and behaviors of complex systems. Over these years, numerous modeling and simulation tools based on the use of software agents have been implemented in the transportation field [26]. With regard to agent-based simulations, they refer to dynamic models based on the action-reaction paradigm and on perceiving a common environment in which agents can communicate, interact and cooperate in order to reveal their emergent behaviors [27]. In detail, "*a software agent is autonomous; capable of operating as a standalone process and performing actions without user intervention*" [28], which during all phases of a problem-solving process is characterized by the ability to take autonomous deliberations to achieve its goals. From a simulation perspective, an agent can adopt a wide range of behaviors from the simplest to the most complex, but the most attractive are based on Belief-Desire-Intention (BDI) approaches [29], i.e., they assume that "*an agent can be identified as having: a set of beliefs about its environment and about itself; a set of desires which are computational states which it wants to maintain, and a set of intentions which are computational states which the agent is trying to achieve*" [30].

Several studies on transportation issues, including MaaS, have been conducted through agent-based simulators (e.g., SimMobility[10], MATSim[11], AgentPolis[12], Janus[13], Urban SIM[14], Polaris[15] and DaySim[16], for instance), and an overwhelming number of simulations have been carried out. A comprehensive overview of these simulators and studies is beyond our scope; however, we cite some of them as an example. An early agent-based simulator is SimMoblity [31]. A simulation platform of the Singapore-MIT Alliance for Research and Technology (SMART); SimMobility embeds several mobility-sensitive behavioral models and includes the capability of modeling of millions of agents covering all transportation stakeholders. SimMobility has also been used in the MaaS study to capture the complex dynamics of MaaS scenarios and business models [32]. A recent study addressed to the identification of MaaS membership attributes is proposed in [33], where an agent-based microscopic simulation for the city of Berlin has been carried out by exploiting the open source software MATSim [34]. Its multimodal transportation system was tested by considering five fare plans and the spatial and temporal distribution of potential customers has been obtained. Finally, a recent investigation of population involvement in new transportation services was conducted in [35] by exploiting another agent simulator, UrbanSim [36], to represent mobility services in the city of Odawara, Japan.

3. The Agent-based Framework

The basic idea underlying this framework is to support travel user choices – before or during their journeys – by identifying suitable mono- or multi-mode services provided by one or more transportation operators in order to obtain integrated mobility services. The optimal service combination solutions might be obtained by considering users' preferences in terms of monetary costs, travel time, comfort, or combinations of them.

The inherently complex nature of MaaS schemes requires detailed representation of the transport services to ensure solutions coherent with user's mobility needs. Generally speaking, travelers move from origin points to destination points by one or more transportation modes in order to satisfy their mobility needs, which arise from the opportunities offered at destination points and not available at origin points. From a MaaS perspective, when a travel is arranged by using multiple transport operators, the several legs should provide similar levels of service and the journey should be realized with a single ticket. In this context, in order to provide digitized traveler mobility solutions, a possible approach is to realize an agent-based MaaS integrated framework where each user is associated with a Personal Agent (PA) interfacing with an Agency (Ag) that, in turn, is interfaced with the agents associated with each transport Operator Agent (OA). In particular, the Agency provides all the agents acting on the platform (e.g., PAs and OAs) with agent directory and communication services, while the PA provides a user with personalized recommendations by a suitable interface on the associated device. The PA would be enabled to interact with all the transport operators (i.e., their associated OAs)

[10]Sim Mobility, https://mfc.mit.edu/simmobility, 2024.
[11]MATSim, https://www.matsim.org,2024.
[12]AgentPolis, https://github.com/aicenter/agentpolis, 2024.
[13]Janus, https://www.janusproject.io, 2024.
[14]Urban SIM, https://urbansim.com, 2024.
[15]Polaris, https://www.anl.gov/taps/polaris-transportation-system-simulation-tool, 2024.
[16]DaySim, https://urbansim.com,2024.

through the Agency, and the user (i.e., the associated PA) would perform in an automatic way all the necessary payments, also including those known as pay-for-use (i.e., like the car-sharing case). Furthermore, each PA will know the most suitable criteria for selecting solutions fitting his/her user's preferences, so that it can suggests those travel combinations – selected among those provided by the Agency that interacts with all the OAs – closer to the user's expectations.

Particularly, each user agent PA is able to select options based on the advantages and disadvantages of each available alternative, because the framework adopts explicitly the hypothesis of "rationality" in simulating user behaviors. Moreover, the proposed framework assumes that all the business and technical requirements are fulfilled (e.g., booking, ticket and payment services) so that the Agency, acting as intermediary between the PA and the OAs, will examine all the possible travel combinations, given by transport modes and their availability at the time when the request is made, and realize an effective integration of services.

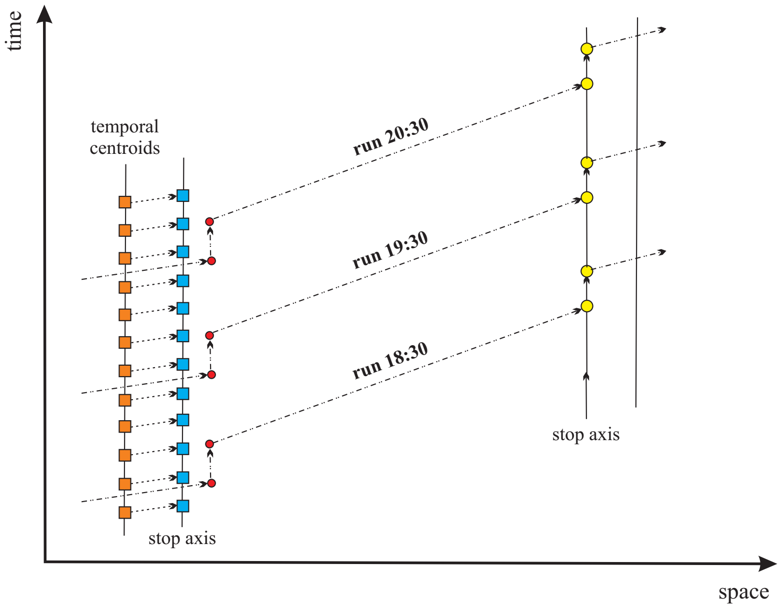

Figure 1: An example of diachronic network.

In detail, the operative plan of the framework consists of some specific steps. Initially, user's preferences are stored in a suitable profile directly managed by his/her PA. Note that in a real-world scenario, such information would be derived both from an initial elicitation process and from the monitoring of user choices by each PA (e.g., trip origin and destination, time, mode choice, comfort, user's preferences). Then, based on the user's transport request, the Agency interacts with each OA in order to receive their transport offers in the form of diachronic networks (see Figure 1). More in detail, the diachronic network (DN) represents the space-time transport service features offered by the OA at the time of the request, $DN_{OA}(t)$. As depicted in Figure 1, the nodes representing transits stop are split into n temporal nodes having the same space coordinates of the real transit stop and as many positions as the number of runs stopping at that (physical) node at a given time in the reference period. The link ("run") connecting two next stops in different space-time positions. Finally, temporal centroids represents user demand split in time, accordingly to the desired departure time, represents the specific run leaving the stop node at time t and reaching the next stop node of its path at time $t + \Delta t$. By overlapping the several diachronic networks starting from time t and at the given space (trip origin), the Agency will identify and select suitable service combinations for linking the desired origin/destination pair and send them to the PA, which will order them based on the user's preferences stored in his/her personal profile. Finally, the PA suggests one or more solutions that might meet user's preferences in the most suitable way, and (in a real scenario) the PA uses the user's choice to update his/her profile.

4. The Agent-based MaaS Simulator

To overcome some limits of existing simulators, mainly in terms of flexibility, the simulator previously developed by the authors, and already applied in [37, 38, 39], has been extended to simulate also diachronic MaaS systems, with the aim to investigate on the potential preferences of MaaS users. The numerical simulator has been written in C++ and it does not implement any Graphic User Interface.

To promote mutual interactions and cooperation activities, in the simulator the Agency and the agents use a message-based mechanism, where messages (having a simplified JADE-like structure[17]) are managed by a Postal Office (implemented by a specific class) and are addressed by exploiting an Agent Directory (AD) service made available by the Agency. Each message includes data on: (*i*) sender, (*ii*) receiver, (*iii*) type of the content (e.g., Information, Trip, Action) and (*iv*) content (e.g., route, preferences, etc.).

The diachronic networks in the MaaS simulator have been represented by adopting a multi-layer approach (see Figure 2). Particularly, layer 0 is associated with the urban map, while each transport service, managed by the associated OA and realized by a given transport mode, is associated with the next layers. More in detail, each layer from 1 to n consists of a diachronic network associated to its OA. For sake of simplicity, all the vehicles associated with a transportation mode (e.g., buses, cars for car-sharing services, bikes for bike-sharing services) are supposed to be homogeneous, which is a reasonable hypothesis because it is expected that such vehicles will have standardized features.

Some information is associated with the nodes and links of each diachronic network in a given layer. Nodes represent the physical points – such as bus stops, car-sharing park lots – where the service is available at a given time. Links represent the time-space relationship between two nodes, e.g. a run for bus services, the travel time between two parking lots for car-sharing services. If the shared service is provided at any physical points in the urban area, links represent potential constraints for the service, e.g., a car-sharing reservation at another time-space point in the network.

Concerning layer 0, the current position of a given user is represented by a node (*origin node*) in the urban map. An area with a radius of $500\ mt$ is considered around the physical position, identified by suitable location devices (e.g., GPS location provided by mobile phones in real contexts). As found in practical applications, the radius of this virtual area represents the

[17] Java Agent DEveloping framework (JADE), https://jade.tilab.com, 2024.

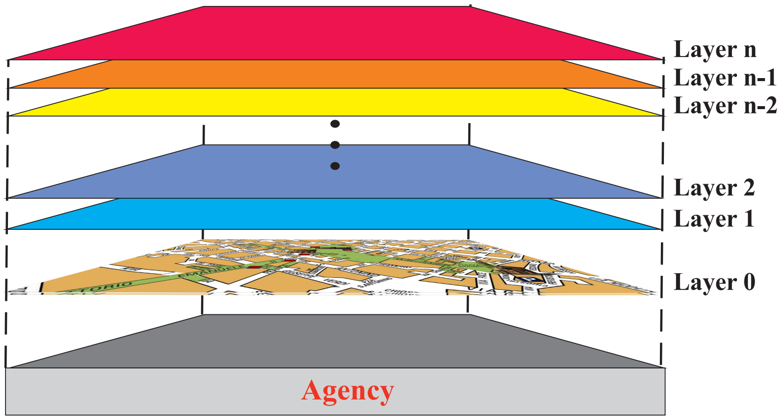

Figure 2: The agent-based framework scheme.

maximum distance the user is willing to walk to reach a place where transportation services are available – e.g., bus stop, car-sharing lot. Note that, layer 0 also considers the space position of stops and places where some shared services are available (e.g., car-, bike- shared systems). When user sends the trip requests to his/her PA, this one asks the Agency for information and sends detail on the user's position. Starting from time t, the Agency select a multi-layer sub-network from the diachronic networks of each layer. Particularly, only services starting at time t or within a time $t + \Delta t$ are considered. The Agency select multi-layer paths, which are sequences of links belonging to one or more diachronic networks in the several layers such that the end node of each link is also the starting node of the next link in the multi-layer path. In addition to the minimum (generalized) cost criterion, some other suitable criteria are used to identify the multi-layer paths, such as topological (i.e., each link belonging to the path moves away from the origin node and/or move towards the destination node), behavioral (i.e., unrealistic paths are excluded, such as the ones bouncing repeatedly between layers), distinctive (i.e., paths should not overlap for more than a given percentage). In order to consider the possible preferences of the user represented by his/her PA, the Agency does not compute a single minimum-cost multi-layer path, but the first n paths with the lowest (generalized) costs. The generalized cost can be based on a single performance variable or their combination – e.g., travel time, monetary costs, but also comfort and safety provided that suitable measures for such variable are available.

It has been stated in several contexts that one of the main goals of MaaSs is to discourage the use of individual-owned car and move users towards shared system, in order to reduce the number of circulating vehicles and possibly reduce negative impacts, such as congestion and environmental impacts. To test this hypothesis, i.e. shift in mode choice, the simulation has been limited to users that are supposed to have their own car and to which MaaS opportunities are offered. Therefore, users choose between their car and one of the MaaS solutions provided by their PA on the basis of the set of options defined by the Agency.

It is worthwhile to note that in a MaaS context users can choose among different modes and different paths, for each mode, linking their origin/destination pair. Generally, such choices depend on both socio-economic features of the travelers and Level of Service (LOS) attributes.

In this framework, traveler's preferences, which embed socio-economic features, are stored in his/her personal profile, while LOS attributes are provided by the diachronic networks of each OA to the Agency, which will search for solutions that could meet traveler's preferences. Therefore, the Agency will identify suitable multi-layer paths that might include more than one transportation mode.

To find multi-layer paths in the proposed framework, the algorithm proposed in [58] is adopted. It is a variant of the Alpha-Beta Pruning [40] algorithm, guided in the depth search by appropriate heuristics to improve the cut-off strategy. The worst-case computational complexity of this algorithm is of b^h in time and $b \cdot h$ in space, where b is the branching factor and h is the maximum depth.

Further features have been introduced in the algorithm with respect to the original form in [41]. In detail, *i*) each link between two nodes in the same layer has been labeled with a tuple, which might store more information in addition to the travel time (provided by each OA); *ii*) the link between layers (i.e., different services and/or transport modes) is characterized only by the waiting time at the commuting point; *iii*) the search horizon of the algorithm, h, may assume values $2, 3, ...n$, which means that, in general, only $1, 2, ...n-1$ commuting modes are allowed; iv) if walking between two commuting points in the same layer is required, which is less than an acceptable walking distance (typically $500\ mt$), the corresponding time is automatically added to the path cost.

Finally, to consider the full potentialities of MaaS schemes, a single ticket should be applied to the entire route between an origin/destination pair. To consider the features of each mode, and the different fares between the use of public transportation systems – like bus or metro – and shared but individual modes – like car/bike-sharing– an additional monetary cost has been applied to paths that include car/bike-sharing, which is greater for cars with respect to bikes. In detail, the car-sharing is considered available at $5\ Euro/h$[18], while the bike-sharing is considered available at $1.5\ Euro/h$. In both cases, subscription to benefit from the service has not been considered. The previous car-sharing fare refers to an averaged values of price applied by companies operating in Italy in several urban contexts (for example, Ubeeqo, operating in Milan). Similarly, bike-sharing fares have been averaged by considering some examples in several Italian cities (again, Milan, but also Bologna, Bari and Rome).

5. Experiments

To test the agent-based MaaS framework, the experiments have been conducted on a simulated urban environment representing a medium-sized city and its transportation network. The road infrastructures of the simulated urban context generate square grids, whose side measures $100\ mt$. This value is coherent with the average urban distances between two intersections in medium-sized urban contexts. To simplify the simulation, without losing in generality, two-way roads have been assumed, with the same lane capacity. This structure represents the base features of layer 0 in the simulator and also the base for private vehicle journeys between origin/destination pairs in the simulated area. Suitable travel times have been associated to each road, based on known cost functions for congested transportation networks (see for

[18] MotoriMoney, https://motori.money.it/Car-sharing-come-funziona-quanto-costa-servizi-Italia, 2024.

example [16]). Note that, the same cost functions apply to the car-sharing network, while for the bike-sharing network travel times have been computed starting from the car network and increasing them by 35% to consider the different speed features.

Concerning the other transportation modes, car-sharing, bike-sharing, subway and bus have been considered. Both car-sharing and bike-sharing services have been considered station-based. Two car-sharing and bike-sharing stations have been located in the map at layer 0 to represents the physical points where the vehicles (cars, bikes) are available. Stops for subway and bus have been randomly located in the map of layer 0, by considering an average distance of 300 mt for bus stops, and 500 mt for subway stations. Some bus lines have been generated by linking sub-sets of bus stops, with the constraints that the average running time between the origin and destination terminus must be grater than 25 minutes and less than 45 minutes. Such line path times have been computed by considering a commercial speed of 15 km/h, which includes all the accessory times due to deceleration/acceleration at stops, waiting time for passenger boarding/alighting to/from the bus and road congestion. Finally, the subway service has been obtained similarly to the bus ones, but commercial speed is greater because of the system features, and it has been assumed equals to 40 km/h.

Still in layer 0, the urban environment consists of a 20x20 square modules, each one of side $L = 500$ mt, whose boundaries are the roads previously designed. This structure, without losing in generality, will allow to consider a modular system. In the center of each module, a demand centroid has been located, which is a virtual point where transportation demand with origin in and/or destination to the module is considered aggregated, accordingly to usual modeling of transportation systems [16]. It is worthwhile to note that in real contexts user location is obtained by GPS (or similar) devices and trips occur between the exact origin and the desired destination. In this simulation, for sake of simplicity and without losing in generality, trips occur between centroids. Origin/destination (O/D) trips have been generated, each trip representing a user request. Trips within the module – i.e., where origin and destination are the same centroid – have not been considered, because under a distance of 500 mt is it supposed that users are willing to walk for reaching their desired destination. By following the aim of this simulation, all users have been considered potentially car drivers and they are provided with MaaS solutions in order to verify potential mode shifts.

Layers 1, 2, 3 and 4 contain the diachronic networks respectively of car-sharing, bike-sharing, bus and subway. Correspondences between different transport services are considered feasible if the connection time – both pedestrian time to reach the point where the transportation service is available and/or waiting time for the transportation service to be accessible – is less than a prefixed threshold (Δt=15 min). Two layers are connected by vertical links if at the time t of the trip request a corresponding service is available. To perform realistic simulations, only two different modes are considered suitable for a given trip, given that users are unlikely to be willing to make more than one within-mode transfer and more than two between-mode transfers. Therefore, the search horizon of the algorithm is $h = 3$.

To summarize, the following assumptions have been considered: *i*) The Agency acquires up-to-date information from the transport operators in order to provide some MaaS trip alternatives to each PA. *ii*) Each trip starts from an origin centroid (O) and ends in a destination centroid (D) placed in different modules. *iii*) For each user (i.e., its PA) the trip request between two centroids ($C^O - C^D$), as well as the associated preferences in terms of time and monetary cost and comfort, have been randomly generated based on some previously available databases concerning user's choices in urban contexts [42]. *iv*) Each trip will combine the available transportation modes to best meet the user's preferences; *v*) Simulations were carried out on three different scenarios (i.e., S_1, S_2 and S_3) at increasing levels of saturation of the private car transportation network at layer 0. Particularly, S_1 being the baseline scenario, for scenarios S_2 and S_3 travel times on the private car transportation network, whose features also applies to the car-sharing diachronic network, have been increased with step $+15\%$ from S_2 to S_3. *vi*) Subway stations, car-sharing and bike-sharing parking lots have been located randomly in the proximity of only a quarter of the centroid points present in the urban context. *vii*) The number of sharing vehicles present at a commuting point could not be sufficient to match a potential transport demand. *viii*) When car-sharing mode is selected at a commuting point, it means that there will be no further commuting operations until the end of the trip. Finally, it is worthwhile to note that in this first experiment attributes as comfort and safety, but also several others, have not been included. Depending on available data, there are no specific limits to the introduction of variables capturing user's preferences.

The simulations were carried out by using the agent-based simulator previously described with reference to a three-hour time interval. 1000 users were considered on the private car transportation network and trip requests for the different destinations have been randomly generated with the constraints that the distances to be covered are not less than 4 modules. The structures of the diachronic networks at layers 1, 2, 3, and 4 have been generated by using rationality and plausibility criteria for linking the stops located at layer 0, while link costs at all the layers have been computed by considering cost functions and average speeds as described before.

During the simulation period, the request of each user has been generated, the paths linking the desired pair $C^O - C^D$ have been computed by the Agency through a minimum path search algorithm [43] and provided to the PA, which lists them based on the stored preferences of its user. The potential shift from the private car to the MaaS solution depends on the probability that the user will consider the MaaS path more convenient than the private car path at layer 0, both suitably weighted to include user's preferences. Usual probability choice models have been considered [16]. For each scenario, the percentage of potential MaaS users who would choose the proposed MaaS alternative is shown in Table 1.

Table 1
Percentages of users choosing MaaS services (results are approximated to the first decimal digit).

Percentage of users (%) Scenario	S_1	S_2	S_3
Private car	100.0	90.7	85.2
MaaS solutions	0.0	9.3	14.8
Combination of public transport and car-sharing	0.0	0.0	0.0
Combination of public transport and bike-sharing	0.0	2.2	5.0
Combination of public transport	0.0	7.1	9.8

As the results show, users' propensity to change their own mode towards shared transport modes increases from S_2 to S_3, i.e. as the congestion level increases. Not unexpectedly, the choice of car-sharing solutions is almost negligible in all the scenarios, which is not surprising. In fact, here car users have been considered, who are rather anelastic in changing their mode unless traffic congestion is strongly increasing. Particularly, as road congestion increases, car travel times increase too and this applies to both owned cars and shared cars. For car owners, the main advantage of shifting to a car-sharing service is that they have not to look for a parking lot, because in the experiment shared cars will be located in the fixed stations. As congestion increases, and parking lot availability might be a real issue, users are more available to consider the car-sharing alternative or public transport alternatives, since in this latter case finding parking lot is not included. As a confirmation, the combination of public transport seems the best appreciated solutions when congestion levels increase.

6. Conclusions

MaaSs represent a step forward in the transformation of urban transport systems, where the shared mobility concept would play an important role with respect to owning a vehicle or depending on a single transport service. MaaSs promote interoperability, data sharing and inclusion to make available a set or interoperable transport services in order to provide a seamless, safe, efficient and fast mobility services. Furthermore, MaaS could encourage the development and adoption of digital technologies and innovation leading to smarter and integrated mobility solutions of different transport operators and services into a single platform.

To this aim, the goal of this paper is to support a user information system in real time, so that the user can choose the most convenient travel combination at the given time, with respect to the opportunities that arise at that time interval. However, users' propensity to change their private mode is an important issue for understanding which is the effective role of MaaS to satisfy mobility needs without providing inefficient travel solutions with respect to features such as travel times and monetary costs, which would penalize users. . In this perspective, in this paper an agent-based diachronic MaaS simulator has been proposed with a twofold aim: *1*) check the effectiveness of a diachronic network approach to simulate MaaS programs; *2*) verify to what extent users would change their private car mode towards shared travel solutions in a simulated agent-based urban scenario. The simulation has been conducted by considering car driver users whose preferences are stored in their personal agent (PA), which receives travel solutions from the Agency – related to transport operators (OA) – and list them accordingly to user's preferences. In addition, three scenarios have been considered, at an increasing level of congestion. The results of the simulation show that users tend to confirm their private car mode choice for low congestion levels, while tend to prefer public transport shared solutions when the congestion levels increase. Although very preliminary, the results show interesting, realistic findings, because they capture the user anelasticity to change his/her private mode towards shared solutions, which is a well-known aspect, unless the disutility linked to the use of the car starts increasing.

Several further developments are expected, both in terms of simulation features and use of real data. Particularly, while in this experiment users have been considered aggregated in Origin/Destination centroids, in further tests they should be simulated randomly located in the map. In addition, GPS-based bike sharing could also be considered and further data coming from Stated Preferences experiments could be used for testing both the introduction of more attributes in addition to LOS attributes and mainly to verify user's propensity to change mode in a real context. Finally, still in Stated preferences (SP) experiments car-sharing and bike-sharing fares will be introduced as factors to be explored, in order to verify user's elasticity towards monetary costs for such services.

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