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Incorporating the Mobility as a Service concept into transport modelling and simulation frameworks

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ABSTRACT

Technological advancements and the rise of the sharing economy have contributed towards the emergence of new flexible and on-demand mobility services and business models with the potential to greatly impact the current mobility landscape. One innovative new mobility concept is Mobility as a Service (MaaS). In this paper, our main goal is to present in detail the MaaS concept, define the MaaS ecosystem's actors' roles, tasks and behaviours and propose an innovative integrated transport modelling and simulation framework that will allow us to capture the complex dynamics of MaaS as well as evaluate its multi-scale and multi-dimensional impact. We explicitly analyse the operational and behavioural functionalities of the integrated supply and demand modelling framework's components, emphasizing the extensions needed to consistently represent the MaaS system's dynamics. Specifically, we propose an extension of an existing agent-based, activity-based, multimodal simulation platform, SimMobility, by incorporating a dedicated controller, the MaaS Integration Controller, which represents the daily operations and decisions of a MaaS Operator. We analyse the multi-scale model interactions within the simulation platform replicating the daily interactions of the system's actors. Finally, we present our future work focusing on the application of the integrated simulation platform for London towards testing MaaS systems with different organizational, operational and behavioural settings.

Keywords: Mobility as a Service, Transport Modelling and Simulation, Integrated Demand and Supply, Operational and behavioural models, personalized on-demand mobility

1. INTRODUCTION

The transportation sector is currently at a juncture characterized by great opportunities and challenges. On the one hand, technological advancements and the rise of the sharing economy have created new opportunities for business models, products and services in the transport sector. New mobility services like peer-to-peer mobility and vehicle sharing, have challenged the taxi and public transport establishment, and personal vehicle ownership. Various Internet companies offer commuter services based on crowd-sourced data, while some automotive manufacturers have only just started capturing internal data from their own vehicles. On the other hand, much of the information currently collected from sensors, vehicles, social media and other sources is locked away in unconnected silos; traffic and transport authorities lack access to raw data from the private sector that could help them improve public services, the efficiency of the transport system and achieve the vision of multimodality[1].

Gathering, analyzing and sharing data in real-time throughout the transport ecosystem can completely reshape the transport experience for people and its impact on communities. Recently, an effort has begun to remove the silos in the transport sector and approach it as an ecosystem. Some regulators seek to cover all transport modes with one unique law, eliminating mode-specific regulation, while also requiring public and private service providers to provide open Application Programming Intefaces (API), enabling the integration of all transport modes into a holistic system which can create seamless travel chains that can be paid for through one mobile system (such regulation is already in act in Finland, while the European Commission is working towards similar regulation for all European Union countries) (*1*).

This changing transport landscape and the need to approach the transport sector as an ecosystem to achieve seamless multimodality and environmental sustainability has triggered the development of the Mobility as a Service (MaaS) concept. "*Maas is a user-centric, intelligent mobility management and distribution system, in which an integrator – the MaaS Operator - brings together offerings of multiple mobility service providers and provides end-users access to them through a digital interface, allowing them to seamlessly plan and pay for mobility*" (*2;3;4*). Public transport modes are usually the backbone in this concept, with convenient solutions offered for the first and last mile of trips which may increase their usage (*5*). MaaS aims to bridge the gap between public and private transport operators and envisages the integration of currently fragmented tools and services travellers currently need to conduct trips. MaaS provides an opportunity for new business and governance models in the transport sector and aims to traverse existing boundaries and silos.

MaaS has the potential to change the mobility market influencing both demand and supply. The seamless, multimodal and personalized mobility offered to end users has the potential to alter their perceptions towards mobility services and personal vehicle ownership and usage, as well as to affect travellers' daily activity, mode and route choices (*5;7*). Moreover, the integration of on-demand services with fixed public transport services for first and last mile trips and intermodal options generates the need to efficiently design and operate the co-ordinated system. Furthermore, given that Maas is conceptualized to promote traditional and new shared mobility options as flexible alternatives to personal vehicles, it could also alleviate congested networks. To capture the real potential of MaaS as well as evaluate and quantify the multi-level impact of potential MaaS implementations, conventional modelling and simulation frameworks and techniques have been found insufficient due to a lack of proper demand and supply interactions representation (*8*). The proper representation of all the demand and supply entities and their dynamic interactions in the MaaS system requires the utilization of integrated demand and supply

[1] "Multimodality" or "multimodal transport" refers to the use of different modes (or means) of transport on the same journey (*6*)

modelling and simulation approaches that explixitly replicate the behaviours and the functionalities of the MaaS system's components. Towards this end, this paper provides a thorough analysis and investigation of MaaS both from a conceptual and a modelling point of view. The main objectives of the paper are to:

1. present in detail the concept of MaaS, the roles, tasks and behaviours of the main MaaS ecosystem actors and review current MaaS deployments around the world;
2. identify gaps in the existing literature in terms of modelling the demand and supply elements of the MaaS concept and propose an integrated transport modelling and simulation framework to model the new dynamics that the different MaaS business models bring to the transport system; and
3. incorporate MaaS-oriented extensions into the integrated supply and demand activity-based model, SimMobility (9).

The rest of the paper is structured as follows. Section 2 elaborates on the MaaS system structure, the MaaS Operator(s) types and reviews current MaaS deployments. Section 3 reviews the latest work on MaaS, identifies gaps in the literature and elaborates on the proposed integrated modelling framework. Section 4 details the integration of the MaaS modelling extensions in the SimMobility platform. Section 5 concludes the paper and provides guidelines for future work.

2. THE MAAS ACTORS AND DEPLOYMENTS

2.1 The MaaS concept, the actors and their roles

MaaS is an ecosystem of interacting demad and supply entities, with a MaaS Operator (MO) in the middle, managing both demand and supply by offering mobility services to end users as well as dispatching/assigning daily trips to several Mobility Service Providers (MSPs; Figure 1). On *the demand side*, MaaS Users (MU) are provided with a list of travel options to choose from, including public and private transport modes, based on multiple needs, preferences and travel budget, as well as a service which allows them to pursue more activities within the same timeline (*8;10;11*). The MUs are also provided with real-time mobility guidance via personalized real-time travel planning alternatives and information. On *the supply side*, the MO is responsible for distributing and assigning trip requests among MSPs, while the MSPs are responsible for the efficient operations of their own services. The provision of a seamless mobility experience to end users is accomplished through the integration of ticketing, booking and payment across several modes.

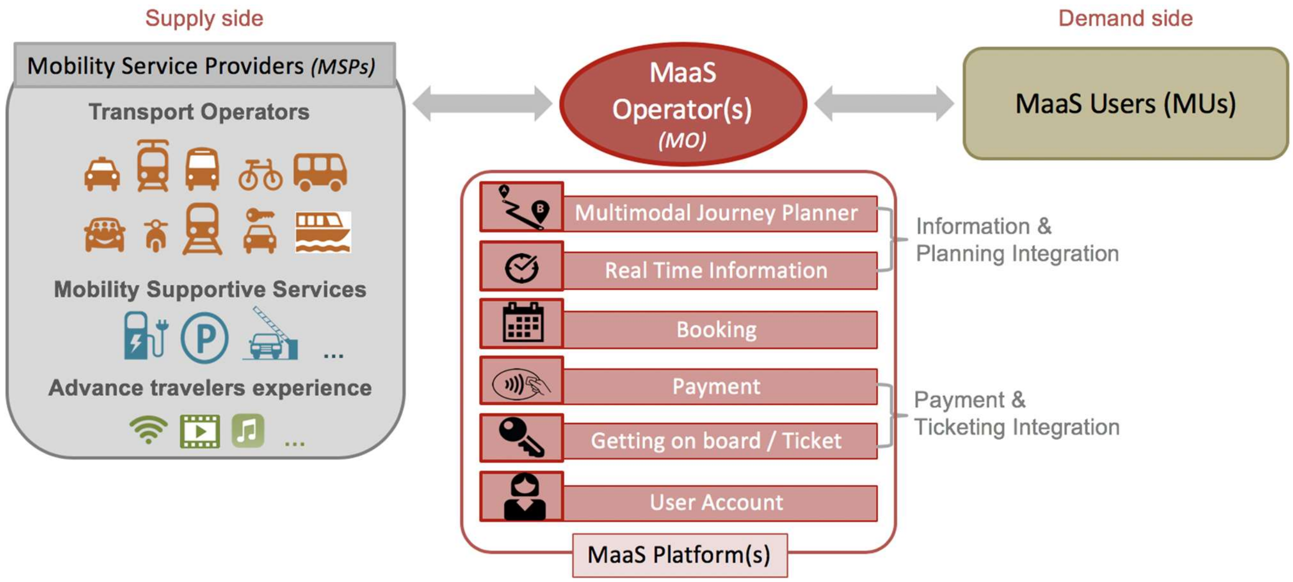

Figure 1: The Mobility as a Service concept

Figure 1 presents a high-level representation of the MaaS core business actors, that are:

- The *MaaS Operator* (MO), the organisation that integrates the mobility service providers' offerings, designs MaaS products by bundling mobility services in different ways, and sells them to end-users. The MO is responsible for determining static and dynamic demand and supply management strategies needed to efficiently run the system. There could be one or several MOs in a given area and an operator can also provide services across multiple areas (however, for simplicity in this paper we refer to one MaaS operator).
- The *MaaS platform* comprising: 1) the computational server responsible for running the daily operations/optimizations for demand and supply management according to the objectives defined by the MO, as well as the system interfacing with mobilty service providers for information, ticketing, booking and payment integration (back-end), 2) the digital interface (i.e. app) used by the end users to access the services, purchase products, plan and book their journeys (front-end). The MaaS platform could be owned by the MO or could be provided by another actor.
- The *Mobility Service Providers* (MSPs) are organizations (public or private) that provide mobility services to the MO and are mainly responsible for managing and operating their own services by focusing on fleet management operations like routing, scheduling, relocation. Services from other providers that could advance the travel experience (e.g. Wi-Fi access or entertainment activities), can also be bundled with the mobility services.
- The *MaaS Users* (MUs) are the end-users that utilize the MaaS platform’s front-end to purchase MaaS products, plan, book and access the mobility services.

The MO is a new player in the transport market. So far, there are three main MO types that prevail in the market and in the literature *(12;13)*. These are:

1. A *private company* that owns no supply assets (fleet etc.); in this scenario, the focus of the MO is mainly to integrate and bundle different public and private mobility alternatives to provide users with the best value proposition for their journeys and mobility. To enhance profit margins and ensure the quality of service, effort is mainly allocated to demand and supply management strategies.

2. A *private MSP* that owns supply assets or controls the supply assets without owning them; in this scenario, the private MSP owns or controls one or more mobility services, but also seeks to partner with public transport service providers and other MSPs to enhance their service promise to customers. It is critical to point out that the MO does not control and operate its fleet via the MaaS Platform. The MSP runs its own operating system responsible for the fleet management operations, while it offers its own services bundled with other MSPs services via the MaaS platform that integrates all information and data interfaces.
3. A *Public Transport Authority* (PTA); in this scenario, the PTA integrates multiple forms of public and private transport through integrated payment and ticketing (in several cities, PTAs are already the integrators of the public transport modes, but in most cases the link to the private modes is missing). As in the 2nd scenario, the MO controls and manages the public transport services via a separate operaring system and not the MaaS platform.

- Demand management operations
    a. *MaaS Products*:The MO is responsible to design the MaaS products that will be offered to the MUs. The products could be either Pay-as-you-Go (PAYG) or plans/bundles of mobility or mobility-related services. MaaS plans provide a static demand management potential in terms of influencing users' mode choices via the type of modes included and the pricing of them.
    b. *Multimodal Journey Planning*: the MO usually offers multimodal journey planning with alternatives of modes and route combinations to MUs as well as real-time information. Real-time travel menu provision can also use a dynamic demand management tool to "nudge" daily demand.
    c. *Dynamic pricing and incentives provisions:* the MO can also dynamically price its services and provide them to MUs that use the PAYG option. Another potential demand management tool is the provision of dynamic reward or penalty incentives (e.g surge pricing, vouchers) for different modes and trips aiming to balance supply and demand, promote underutilized modes or even "greener" options.

- Supply Management operations
    a. *Trip assignments to MSPs:* the MO is responsible for assigning and distributing users' trip requests to different MSPs as well as providing daily static or dynamic demand predictions to MSPs aiming towards the increase of the level of MaaS-services in a win-win situation.
    b. *Integrated payment, booking, ticketing*: the MaaS platform is used for all the payments, bookings (if required) and enables users to access tickets for their desired mode of transport.

- Fleet management operations
    a. According to the second and third MO types (MO is an MSP), the MO might control and operate a service-specific vehicle managing the fleet directly; in this case the MO may also perform fleet management operations depending on the service (PT, taxis, new mobility services like carsharing, ridesharing, ridehailing, etc.; but this is not part of the MaaS Platform).

2.2 MaaS Deployments

Over the last few years, several demonstrations have been initiated to provide insights about what is needed to materialize MaaS. In addition to early pilots, commercial implementations have also been launched recently incorporating several of the above functionalities. Currently, we have identified fifteen MaaS demonstrations around the world. The criteria used for identifying MaaS demonstrations are integration of public and private transport modes in terms of planning, booking, ticketing and payment. As mentioned above, the MaaS concept aspires to overcome the silos in the transport sector aiming to create an efficient, seamless and sustainable transport ecosystem. As such, intermodal journey planners without the option to pay for or access different transport modes and only public transport integrated systems are not considered as MaaS demonstrations. The demonstrations are summarised in Table 1.

Table 1: Review of MaaS Deployments

	Company (Region of Operation)	**Date & status**	**Provided Services**	**Modes Integrated**	**MaaS Operator Type**
1	Go-LA (Los Angeles; *14*)	2016 - Operational	Planning Booking for Parking	Public: Bus, Rail Private: Bike-sharing, Car-sharing	PTA
2	Jakdojade (Poland, Warsaw; *15*)	2018 - Operational	Planning Ticketing Payment	Public: PT Private: Bike-sharing	Private company owning no fleet
3	Mobility Shop (Hannover; *16*)	2014 - Operational	Booking Ticketing Payment Mobility plans	Public: PT, Rail Private: Car-sharing, Taxi	Private company owning no fleet
4	Moovel (Germany; *17*)	2016 - Operational	Planning Booking Ticketing Payment	Public: PT, Rail Private: Bike-sharing, Car-sharing, Taxi, Ferry	Private MSP owning fleet and collaborating with PT and other MSPs
5	MyCicero (Italy; *18*)	2015 - Operational	Planning Booking Ticketing Payment	Public: Bus, Metro, Rail Private: Taxi Parking, Congestion charge + Entertainment: Cinema	Private company owning no fleet
6	Navigogo (Scotland; *19*)	2017-2018 Pilot concluded	Planning Booking Ticketing Payment	Public: PT, Rail Private: Taxi, Bike-sharing, Car-sharing	Private company owning no fleet
7	Smile (Vienna; *20*)	2014-2015 Pilot concluded	Planning Ticketing Booking Payment	Public: PT, Rail Private: Bike-sharing, Car-sharing, Taxi, Parking, Charging, Ferry	Private company owning no fleet

8	SWITCHH (Hamburg; *21*)	2013 - Operational	Planning Booking Ticketing Payment	Public: PT Private: Bike-sharing, Car-sharing	Private company owning no fleet
9	TransitApp* (Montreal; *22*)	2018 - Operational	Planning, booking/hailing and payment only for ridehailing	Public: PT Private: Bike-sharing, Car-sharing, Ride-hailing, Scooter-sharing	Private company owning no fleet
10	Tuup (Kyyti) (Turku, FI; *23*)	2015 - Operational	Planning Booking Ticketing Some payment	Public: PT, Rail Private: Bike-sharing, Car-sharing, Car-rental, Taxi, Ride-sharing	Private company owning the on-demand bus fleet
11	UBER** (San-Francisco; *24*)	Planning phase		Public: PT Private: Bike-sharing, Scooter-sharing, Ridehailing, Carpooling	Private MSP owning part of the fleet and collaborating with PT
12	Ubigo (Gothenburg; *25*)	2014 Pilot concluded	Booking Payment Mobility plans	Public: PT Private: Bike-sharing, Car-sharing, Car-rental, Taxi	Private company owning no fleet
13	Urbi (in 26 EU cities; *26*)	2014 - Operational	Planning Booking	Public: PT Private: Bike-sharing, Car-sharing, Scooter-sharing	Private company owning no fleet
14	Whim (Helsinki-UK, Birmingham-UK, Antwerp-NE, Amsterdam-NE; *27*)	2016 - Operational	Planning Booking Ticketing Payment Mobility Plans and PAYG	Public: PT, Rail Private: Bike-sharing, Car-rental, Taxi, Ridehailing	Private company owning no fleet
15	WienMobil (Vienna; *28*)	2015 - Operational	Planning Ticketing Booking Payment	Public: PT Private: Bike-sharing, Car-s haring,Taxi	Public Transport authority

*TransitApp is a multimodal journey planner and is available for more than 140 cities around the world. In Montreal, TransitApp provides trip planning recommendations combining public and private modes, while it also allows users to hail and pay for a Teo taxi. Source:https://transitapp.com

** UBER operates as a ridehailing company. In San Franscisco, UBER acquired JUMP, a bike-sharing company, and invested on Lime acquiring access to the Lime scooters and bikes. It also collaborates with Masabi to develop a ticketing system to have access to public transport. UBER is planning to integrate its ridehailing services with other private modes and public transport modes in San Francisco.

Source:https://angel.co/newsletters/all-aboard-the-scooter-bandwagon-071218?email_uid=679800885&utm_campaign=platform-newsletter-071218&utm_content=view-online&utm_medium=email&utm_source=platform-newsletter&utm_term=

Based on the review presented in Table 1, most of the MaaS services are offered by private companies that own no fleet, while in most cases multimodal journey planners are converted into MaaS services offering booking and ticketing in addition to planning. There are also cases, where MSPs integrate public transport options in their offerings, but the cases where a MSP collaborates with other MSPs (competitors) are rare. Finally, there are some cases where the PTA acts as the MO.

3. MODELLING MAAS IN AN INTEGRATED TRANSPORTATION MODELLING AND SIMULATION FRAMEWORK

MaaS has faced an upward trend and a continously increasing popularity. Several MaaS business models have already been implemented the last years and more are expected to emerge. The potential benefits associated with MaaS, both from a user side (flexibility, convenience, affordability, demand responsiveness) and a city-perspective side (congestion alleviation, reduced emission levels, increased accessibility), has resulted in the emergence of research studying some elments of the demand or supply of MaaS via modelling, simulation and optimization.

From a user perspective, recent studies have addressed the potential impact of MaaS on individuals' daily travel behaviour and choices. Noekel and Oliver (29) presented an extension of the traditional 4-step travel demand model to incorporate MaaS in the PTV Visum software by considering MaaS as an additional mode of transport like carsharing or ridesharing; however, MaaS is not a transport mode alternative. Friedrich and Noekel (*30*) proposed an extended macroscopic dynamic and schedule-based transit assignment model to capture travelers' mode and route choices in integrated vehicle sharing and public transport systems. The access to better information and more travel options that MaaS promises has the potential to affect not just the modes by which MUs travel with but also their daily activity plans (*31;32*). This potential multi-dimnesional impact of MaaS has also been addressed by Jittrapirom et al. (*8*) who point out the necessity of activity-based travel demand modelling approaches to capture the complicated interactions between MUs and the multitude of decisions they face. Finally, another dimension of Maas has been examined by researchers who focus on understanding individuals' subscription and MaaS product choices and their potential to affect the levels of demand for different mobility services (*7;33;34;35;36*).

From a supply perspective,, an extensive amount of research has also focused on the supply elements of MaaS in terms of the efficient design and operational features of integrated mobility systems that are based on the integration of new mobility services with fixed mass transit systems. The increased accessibility and flexibility of integrated mobility systems that utilize on-demand and shared mobiliy services for first- and last-mile connectivity has been investigated by researchers who considered services like bikesharing (*37*), ridesharing (*38;39*) and autonomous vehicles (*40;41;42;43*). The main focus of the aforementioned studies is the investigation of operational parameters and requirements in terms of efficient integrated system designs via the combination of modelling, simulation and optimization approaches. Differentiating from previous studies that considered integrated new mobility services with mass transit systems, Atasoy et al. (*44;45*) proposed a new concept, the Flexible Mobility on Demand (FMOD) is conceptualized as a demand responsive and flexible alternative to fixed-route and schedule-based mass transit services, integrating taxi, shared taxi and mini-bus services. The problem of travel planning in multimodal networks has also been extensively studied by addressing either planning based on traditional transport modes (*46*) or combination of traditional and new (*47;48;49*).

MaaS is a system of active and continuously interacting demand and supply entities, in which the MO acts as mobility demand manager and distributor. From a modelling perspective, the system's fundamental dynamism and complexity requires comprehensive representation of the core MaaS actors (MO, Mus, MSPs; see Figure 1) as well as their interactions, functionalities and behaviours. While existing research has addressed various MaaS related business models and integrated systems, further research to explicitly represent the operational and behavioural dynamics of the decentralized system of MaaS under different organizational and operational settings is needed. Within a MaaS system, operations required to efficiently run the system are centrally managed by one operator, rather than several (MOs and MSPs), and are characterized by demand, supply and fleet management strategies and decisions. Additionally, an explicit representation of the dynamic and mutli-scale individual travel behaviour allows complete and consistent evaluation of the impact MaaS has on daily activity and travel patters. The utilization of integrated modelling and simulation techniques is deemed necessary to conduct a consistent analysis and evaluation of different MaaS business models, MO types and their implementations in urban environments from both business and transportation perspectives. MaaS modelling and simulation requires the following particularities:

1. Explicit demand modelling for individuals in agent-based frameworks aiming to capture the impact of MaaS availability, products and performance in long-term choices like vehicle ownership, subscription and product choices as well as in daily choices like activity participation and mode/route choices;
2. Explicit representation of the daily management operations and decisions in the system for both MOs and MSPs under various strategies and coordination settings;
3. The consideration of the interactions between the models of the integrated framework to reproduce the information and data communications between the MO, the MUs and the MSPs.

Therefore, we propose an Integrated Transportation Modelling and Simulation (ITMS) framework developed explicitly to replicate all the daily operations, interactions and behaviours of the MaaS system's actors (Figure 2).

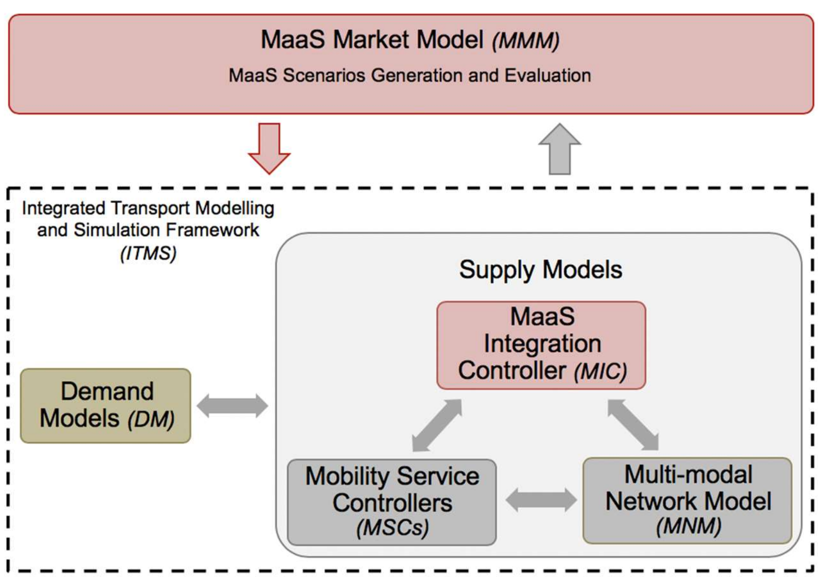

Figure 2: General integrated transport modelling and simulation framework

Five major components are required as part of the system to model MaaS:

1. The *MaaS Market Model* (MMM) responsible for setting the ground of the MaaS scenario simulation, establishing MaaS system-related features and configurations as well as evaluating the MaaS system's performance.
2. The *Demand Modelling framework* which is a system of econometric demand models responsible for capturing MU's (referred to as agents within the simulation) long-term and short-term choices.
3. The *Multi-modal network model* which handles aggregated or disaggregated vehicle movements in public and private transport networks.
4. The *MaaS Integration Controller* (MIC) which is a module that replicates the MaaS platform's daily operations.
5. The *Mobility Service Controllers* (MSCs) which are dedicated modules that replicate the individual service management operations performed by public or private MSPs.

In the following subsections we analyse the ITMS framework's components in greater detail, focusing mainly on the extensions needed to capture the new dynamics of the MaaS concept.

3.1 MaaS Market Model

The MMM represents the MaaS business ecosystem within the ITMS framework. It provides the basis for establishing a given simulation configuration by capturing offline settings from long-term decisions of the MO. The MMM provides inputs to the simulation framework and takes outputs from the simulations to evaluate MaaS performance and understand the strengths and weaknesses of elaborated scenarios.

Scenarios are generated and configured based on MO types and the key functionalities, partnerships and commercial agreements with MSPs. This configuration is developed based on how a MO would operate within the ecosystem, considering how value will be created, captured and delivered to customers. First, the MO's role, priorities and objectives are defined (e.g. profit, air quality, congestion etc.). Identification of the MO's objectives will consequently be aligned with the demand and supply management strategies required to achieve those objectives. The range of prices for MaaS products and MSP services are established on the basis of market conditions taken for the scenario under consideration. The agreement of responsibilities between the MO and MSPs should be outlined within the generation of the scenario so that the appropriate relationships can be established within the modelling framework. For example, the extent of data sharing between MOs and MSPs affects the flows within the model. These agreements vary between scenarios and affect how the *MIC* interacts with *MSCs* and agents. Finally, the policy framework and strategic plans for the transport system are considered. Through a configuration file, the generated MaaS scenario is provided to the ITMS so that the appropriate models and specifications are run.

The MMM also evaluates the results of the simulation for each scenario so that the expected results of the configuration can be fed back to key stakeholders: potential MOs, MSPs interested in MaaS and the local government responsible for regulating MaaS. This allows stakeholders to make informed decisions towards implementing MaaS. KPIs of interest to each stakeholder are defined and measured. The profitability, revenues and costs of the MO will be analysed to assess the strengths of the business model. The added value of certain services helps determine where the MO should focus their efforts. The impact of providing services through a MaaS system (increase in trips, revenue, costs) for MSPs is important to determine what agreements can be made between the MO and the MSP in terms of capacity and pricing.

MO's goals within the policy context provided through the scenario should be evaluated to see whether MaaS can help achieve societal goals set out by policymakers. The results of the evaluation can be further used in the generation of scenarios for future simulations to better test the strengths and weaknesses of a MaaS system.

3.2 MaaS Integration Controller

According to Figure 3, the *MIC* lies in the centre of the ITMS framework interacting with both agents and the *MSCs*. The *MIC* is a simulation-based module designed explicitly to integrate and replicate key operational decisions performed by the MO's MaaS platform to orchestrate the MaaS system as well as the information and data communications with the system's components. Each module in the *MIC* focuses on different tasks and problems. The *MIC* is composed of the *MaaS Integration Optimizer*, which is the control centre of the *MIC's* main management and distribution operations, and the *MaaS Integrated Interface*, which represents the interfaces of the MaaS platform with both MSPs and MUs. The integration of different *MIC* operations under one framework will allow us to develop a tool for the evaluation of how different business models and operational strategies might impact the MO and MaaS system performance. The *MIC* components and its functionalities are outlined in detail below.

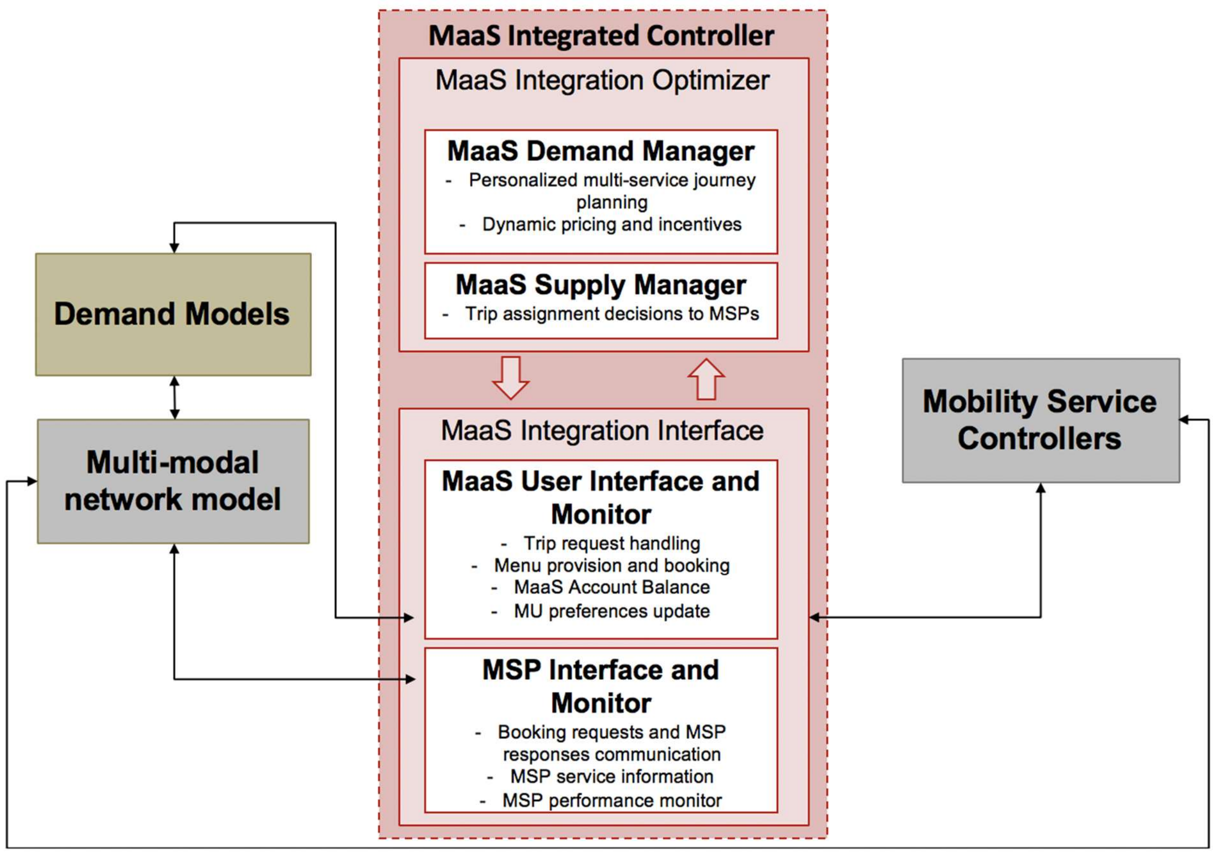

Figure 3: MaaS Integrated Controller General Framework

- <u>MaaS Integration Optimizer (MIO)</u>

The MaaS Integration Optimizer is the mobility management and distribution centre of the MaaS system. The optimizer consists of two main submodules; the MaaS Demand Manager and the MaaS Supply

Manager.

- MaaS Demand Manager

From its inception, the user-centric concept of MaaS was conceptualized in a way to address, among others, the challenge of personalized and flexible multimodal urban mobility. Allowing travellers to seamlessly plan and book their daily trips in a multimodal network is regarded as a key MaaS requirement, and thus, the provision of multimodal journey planning alternatives and the ability to book trips with several modes are elements integrated in the MO's services. By disseminating personalized real-time mobility guidance to MUs, the MO is provided with the potential to manage the daily MaaS demand more efficiently, optimize the transport network and improve vehicle capacity utilization. Therefore, an indispensable component of the MIC's modelling framework is the *MaaS Demand Manager* which is a demand-responsive management tool tailored to the context of MaaS. Its main responsibilities are:

1. generating a menu of personalized travel alternatives to MUs considering their historical choices and preferences, current and future network conditions, MSP real-time service information, and MU's products and account balance.
2. managing demand for different mobility services in real-time by applying pricing and incentive strategies and satisfying the objectives defined by the MMM and the corresponding scenario

The multimodal journey planning process in the system of MaaS is a complex optimization process that requires integration of information from both the demand (MUs) and the supply side (MSPs) aiming towards the generation of a personalized menu of travel alternatives. The problem of personalized menu optimization and the potential benefits associated with it for both mobility service operators and customers has been studied by Song et al. (*50*) and Atasoy et al. (*44*). In a similar fashion, *MaaS Demand Manager* will tackle these challenges by incorporating an optimization framework that will utilize static and dynamic information from MU-agents (e.g. trip origin and destination, preferred departure time and arrival time, mode preferences, MaaS Account details etc.) and MSPs (e.g. service vehicles location, availability, capacity, timetables, etc.) as well as current and future network conditions. The main objective of the optimization problem will be to produce travel options that maximize consumer surplus and/or MO's profit.

Additionally, the *MaaS Demand Manager* will be also based on optimization approaches accounting for different dynamic pricing and incentive strategies performed by the MO to achieve its objectives. Real-time demand management schemes are vastly used in the transport sector since the latest advancements in Advanced Traveller Information Systems and Advanced Traffic Management systems (*51;52;53*). The emergence of decentralized mobility platforms connecting travellers to service providers/drivers, i.e. UBER and LYFT, has resulted to new demand management strategies such as dynamic pricing (*54;55*), which aim to balance daily travel demand and supply. The objectives of the dynamic pricing/incentives strategies implemented in the MIC are directly related to the MO's role and objectives which will be configured by the MMM. According to the MaaS scenario, different objectives can be tested and implemented including MO's profit maximization, promotion of underutilized or shared modes, promotion of mass transit options, promotion of environmentally friendly travel options, etc.

- MaaS Supply Manager

MaaS is a decentralized mobility dispatching environment in which the MO is subject to distribute the demand and assign booking requests to different MSPs. More specifically and based on the premise that the MO "procures" real-time demand for a mobility service to more than one MSPs that offer this specific type of service, the *MaaS Supply Manager* replicates the MO's assignment strategies and decisions. Consider a scenario where a MU makes a request for a taxi trip that will take her/him from A to B, and the MaaS system incorporates more than one taxi providers. In such a case, the MO is faced with the challenge and provided with the flexibility to assign the taxi trip to one of the potential taxi providers in the MaaS system. Therefore, the assignment of customer service requests to MSPs is a result of a dynamic optimization process that will reflect the tradeoff between the MO's profit/objectives and the level of service.

- <u>MaaS Integration Interface</u>

The MaaS Integration Interface represents the front-end or otherwise the interfaces of the MO's platform with the MaaS ecosystem's actors. It is a module responsible for handling all the data and information communications between the MIC, the MUs and the MSCs as well as the dynamic monitoring of the activities and performance of both MUs and fleet vehicles. *MaaS Integration Interface* is composed of the *MaaS User Interface and Monitor* and the *Mobility Service Providers Interface and Monitor*.

The *MaaS User Interface and Monitor* is mainly responsible for:

1. Receiving and handling real-time journey planning requests from MUs like origin, destination, preferred departure and arrival time.
2. Presenting the menu of journey planning alternatives to the MUs upon each request
3. Providing the potential of booking uni-modal or intermodal trips.
4. Tracking MU's activities like pick-up time and location, drop-off time and location.
5. Monitoring and capturing the dynamic daily usage of the MaaS Plans by keeping track of the remaining miles/trips for each service included in the plan (MaaS Account Balance). Each user's dynamic MaaS Account Balance will be considered from the MIO for the generation of the personalized menu.
6. Monitoring and capturing the daily mobility choices and preferences of the MUs that will allow the MIC to increase the personalization of the service provided.

The *Mobility Service Providers Interface and Monitor* is mainly responsible for:

1. Interfacing with the MSCs and collecting real-time service information required to generate a menu of travel alternatives (e.g. fleet vehicle locations, availability and capacity, timetables, etc.).
2. Communicating MU's booking requests to MSCs and capturing MSP's responses like acceptance or rejection of the request.
3. Monitoring and capturing real-time traffic information provided by potential ATIS can be emulated via the multi-modal network model.

3.3 Demand Modelling Framework

The application of conventional simulation platforms to model and evaluate MaaS entails limitations mainly due to the complexities it places on travel demand. The evaluation of future MaaS scenarios and business models requires their emulation on an ITMS framework which needs to account for the consistent representation of agents' daily activity and travel patterns as well as their decisions in the MaaS system. Capturing the impact that MaaS may have on when and how people travel requires a disaggregated demand modelling framework accounting for individual's preferences and needs as well as the impact of the personalized services that MaaS offers.

Initially, the choice of subscribing to MaaS is a long-term decision, linked closely to key characteristics such as vehicle ownership, residential and work locations. Understanding which individuals would choose a MaaS plan or the pay-as-you-go option provides the opportunity to demonstrate which markets MaaS Operators should initially target and how the network may be affected in the long-term (*33*). The choice of subscription to MaaS further affects people's behaviour throughout the day, necessitating for the analysis of individuals' daily activity patterns. Since the new convenient access to multiple transport modes could provide users with the same level of service as a private car (*31*), understanding the whole daily pattern is critical. The further integration of IT, social networks, journey planners and information all needs to be captured in order to assess how MaaS could change travel demand. As such, further innovation in terms of daily activity schedules as well as subsequent models such as destination and mode choice models need to be included. The intermodal nature of MaaS also necessitates the more detailed breakdown of trip planning through stage-by-stage analysis to capture the full trip chain and route choice process.

The multi-scale interaction between the *MIC* and the *demand modelling framework* is necessary towards the identification and estimation of demand levels for different modes that emerge in the transport network. Such interaction and proper demand represenation will enable decisions makers like transport planners, public transport authorities and MSPs to capture the potential impact of MaaS on on-street parking demand, infrastructure requirements, PT attractiveness, fleet size requirements, pricing policies, etc.

3.4 Multi-modal network model

An important requirement for the ITMS framework is emulating fleet vehicle movements in the network as well as dynamic network traffic conditions for different time periods (peak and off-peak). The development of an integrated tool replicating vehicle trajectories and traffic conditions will allows us to capture the impact of dynamic network conditions on agents' travel behaviour and the impact of operational policies and strategies applied from the *MIC* and *MSCs*. Therefore, an indispensable component of the ITMS framework will be a *multi-modal network model* which will represent both public transport and road networks, emulating vehicle movements and traffic flows.

Several network models and traffic flow simulators can be seen in the literature (*56*) which are mainly categorized according to their abstraction levels, macroscopic, microscopic and mesoscopic (*57*). The level of detail of the network model plays an important role in the proposed ITMS framework as it needs to represent physical objects like individual vehicles and drivers with their movements and decisions. Thus, the network model will be based on either microscopic or mesoscopic simulation approaches. Microscopic modelling of traffic flows captures the explicit motion of each vehicle in the network. Disaggregate vehicle motions are emulated via models representing drivers' decisions in response to surrounding traffic, including car-following and lane-changing models. On the other hand, mesoscopic traffic flow simulators take advantage of individual vehicle representation of microscopic simulation but utilize simplified traffic flow dynamics aiming towards lower data requirements and higher computational efficiency.

Seeing as the *MSCs* might influence the movements of service fleet vehicles in the network (e.g. assignment, routing and relocating orders), the above modelling approaches will enable us to utilize a network model that emulates dispatching activities and orders performed by different MSPs towards either drivers or vehicles. The network model will provide tracking functionalities for real-time vehicle fleet movements exchanging location and status data with *MSCs* and the *MIC*.

3.5 Mobility Service Controllers

The explicit representation of the strategic, tactical and operational decisions and activities as well as different communication interactions between MSPs and their respective fleets are captured via the *Mobility Service Controllers*. *MSCs* are modules acting as the central control point of a mobility service; they are responsible for day-to-day management and coordination of fleet vehicles aiming to offer efficient services to customers. In the context of MaaS, *MSCs* will not have direct interaction with potential MUs/agents. As above, the *MIC* acts as an intermediate between MUs and *MSCs*/agents receiving, managing and dispatching service requests and responses to both sides.

Several traditional and new mobility services and their operations, like fixed PT services (Bus, rail, metro, tram), traditional taxi services and new mobility services (carsharing, ridesharing, bikesharing, AMoD, etc.) can be represented by *MSCs*. *MSCs* utilize static (station locations, parking locations, vehicle fleet size and composition, etc.) and real-time (vehicle location data, vehicle speeds, vehicle status, etc.) information by interacting with drivers and vehicles in the multimodal network model. Its main objectives are to identify static or dynamic operational decisions needed to run the service, satisfy demand and communicate potential dispatching and routing decisions to vehicles/drivers in the network model. The functionalities of each *MSC* might differ as they are dependent on the type of service. In the literature the main planning and operational decisions considered include station locations, fleet sizing, static pricing, scheduling, assignment, routing, inventory rebalancing, fleet relocation and redistribution, dispatching, dynamic pricing and vehicle tracking activities.

4. SIMMOBILITY AND MAAS INTEGRATION

According to the integrated MaaS demand and supply modelling and simulation requirements explicilty addredded above, we propose the integration of the MaaS framework in an *ITMS* that consists of the fundamental design and agent-based demand and supply modelling approaches needed to consistently model and evaluate MaaS. This section presents the modelling architecture for the integration of the MaaS framework with a state-of-the-art *ITMS*: SimMobility (*9*). SimMobility is an agent-based, activity-based, multi-modal simulation platform that models individual travel decision-making and the transportation systems operations at different time-scales. It integrates various mobility-sensitive behavioural models with state-of-the-art scalable supply simulators to predict the impact of demand on transportation networks, smart mobility services, travelers accessibility and the environment.

It is comprised by three different simulation levels: Long-Term (LT), Mid-Term (MT), and Short-Term (ST) corresponding approximately to the traditional land-use (LT), travel demand and mesoscopic network (MT) and microscopic traffic (ST) simulation models. However, it brings several state-of-the-art demand and supply modelling formualtions along with the fundamental consistency across levels when future transportation scenarios are at stake. SimMobility-LT predicts the changes on land use and economic activity by capturing individual choice decisions on housing, job, land development and car ownership at every large time step (i.e., months to years). SimMobility-MT simulates day-to-day individual activity and travel demand, including mode, destination, route and departure time choices. Furthermore, agents' movements are captured at aggregate level in MT with a multi-modal dynamic traffic assignment supply simulator. Finally, SimMobility-ST has a high-resolution vehicle movement model, such as driving acceleration and lane-changing, along with detailed control decisions at a microscopic (less than second) granularity. SimMobility establishes feedback loops between the demand-supply of each of these three levels. For example, SimMobility-ST uses trip chain generated by SimMobility-MT, which is also generated by using land use information from SimMobility-LT. The agent travelling the actual network at microscopic network level is generated based on the land use and travel demand models in higher levels. After that, the demand of higher level is updated by the network performance from the detailed simulator through the feedback loop in the next run. Introducing new mobility solutions such as a MaaS scenario would affect aforementioned traveler's choices, including mode choice or vehicle ownership, thus making this integrated framework extremely attractive for MaaS design and assessment.

Recent studies relied on the *mobility controllers* simulation feature of SimMobility to study future scenarios. The core of this feature is the development of flexible interfaces between the different *mobility controllers* and the multi-layers and demand and supply agents and entitites of SimMobility. These *mobility controllers* can replicate the operations of different mobility providers, public transportation (*57*) and urban rail operators, (*58*) or Smart Mobility providers (59*;60*).

Here, we propose the implementation of the *MIC* that will interact with the demand and supply (other controllers and the network) agents and entities of SimMobility. The MO is ultimately part of the overall supply simulator of SimMobility, however having each fundamental (decision making) module detachable for flexible simulation of different MaaS business models.

Figure 4 presents the overall integration framework. At the top is the *MMM* configuration: wh a set of input files where longer-term MaaS products, partnered MSPs and demand-supply exchange rules are defined. It is also responsible for capturing the overall key performance measures that can be used to evaluate the simulate configuration. The latter is a key link to the first modelling "layer" of interactions within the simulation. As discussed above, the MMM is a dynamic component of the MaaS ecosystem as it evolves over time, with the release of new MaaS products from the MO, new MSP contract agreements in reaction to business opportunities or MO daily operational setups all in reaction to demand or supply performance changes. This first modlling "layer" covers the long-term decision making from both demand and supply agents:

- An agent in SimMobility LT - an individual within a household - will face the decision of subscribing (and switching or unsubscribing) to a MaaS system as well as choosing one of the offered MaaS products available. The time step of this decision-making fits similar patterns with the existing subscription decision making for other smart mobility services in SimMobility, such as public transportation or MSPs, i.e. from monthly to yearly. The agent in SimMobility LT will consider, among other attributes, the performance of available packages, according to her/his household travel needs. Finaly, existing long-term choices in SimMobility LT, such as vehicle ownership, location or other subscription models need to be re-estimated to consider the presence of MaaS products.
- A supply agent, such as a MSP, simulated in SimMobility as a controller can also make long-term decisions on partnerships with the MO, by entering in or withdrawing from MaaS, as well as changing service agreement details (e.g. price or capacity levels available to MaaS). These are new long-term modelling needs within the existing SimMobility framework.

- Finally, the MO supply agent can also review the general rules of daily operation, for example the available capacity or price structure due to any changes based on the above.

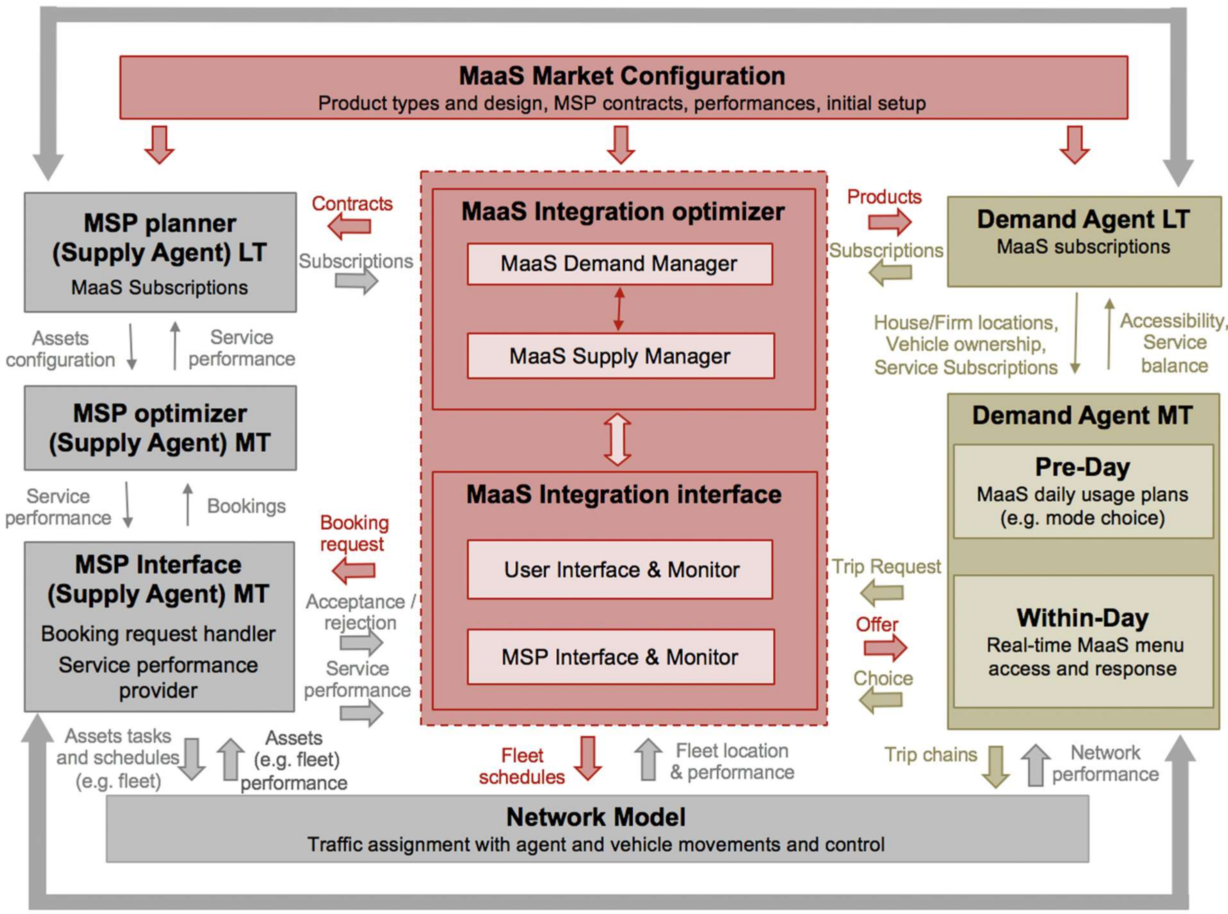

Figure 4: Simulation framework of MaaS integration in SimMobility

The second "layer" of modelling interactions happens on the daily decision making and supply simulation, i.e. the SimMobility-MT model. On the demand side, the set of LT decisions above will create a set-up for SimMobility-MT pre-day module, where the planned daily activity schedule for each agent is computed through a sequence of choice models, resulting in a set of planned activities with corresponding times, together with the main transport modes selected between activities (including the MO alternatives and its daily performance in terms of average travel times, costs and other attributes across the different products). These form the key demand input for the within-day simulation, where demand in terms of actions and schedule revisions are carried out by agents as they interact with the supply models. Here, agents with trips planned from the MO (or within-day mode choice revisions) will access the MaaS Integration Interface for trip requests, for consultation of their journey planner and for choice of the prefered offering from the MO, which can be computed in real time by the MaaS Integration Optimizer. Finally, SimMobility's network model (either SimMobility-MT mesoscopic dynamic network assignement or SimMobility-ST microscopic simulator) will move the agent according to their selected trip through the simulated operations of the MSPs. Indeed, the second "layer" of modelling interactions also accounts for the operational interactions between the MO and the multiple MSPs that form a given MMM scenario. When an agent has selected a given offering, the MO optimizer will decide on the MSP to service this request and will transfer it acordingly. The MSPs, which will be represented in the simulation by its dedicated controllers, will then include it in their operational algorithms for servicing or, possibly, rejecting the booking request.

Finally, the bi-directional grey arrows at the top and bottom of Figure 4 represent the interactions between demand and supply agents outside the MaaS ecosystem. These will allow simulation of the complementary and competitive effects of MaaS in today's multimodal mobility systems and compute complete performance measures at the level of the traveler, multiple operators and the network.

5. CONCLUSIONS AND FUTURE WORK

This paper presented an analysis of the MaaS concept, identified the MaaS ecosystem's core actors, their roles, responsibilities and behaviours and proposed a conceptual integrated modelling and simulation framework to capture the multiscale dynamics of the MaaS concept and its potential implementations. The integrated framework is conceptualized in a way to enable policy makers to test different MaaS business models with different organizational, structural and behavioural settings and evaluate the potential multiscale and multidimensional impacts of MaaS. We explicitly analyzed and proposed specific extensions to an existing integrated modelling and simulation framework, SimMobility, that allow us to emulate the management and distribution decisions that take place in the MaaS platform as well the operational decisions from the MSPs. Finally, we presented and described the complex models' interaction that take place in the MaaS modelling and simulation framework on a long-, med- and a short-term basis.

Regarding future work, we are planning to test and evaluate different MaaS business models with different configurations settings by developing the required MaaS-oriented extensions in SimMobility and apllying the integrated modelling and simulation framework for Greater London. The development process will include extensions of the existing long-term and activity-based modelling framework in SimMobility accounting for the long-term and short-term decisions that the MaaS ecosystem's actors make. The demand modelling process will be based on state-of-the-art data collection processes as well as innovative econometric modelling approaches. Moreover, an important part of the development process will be the design of the MaaS Integrated Controller, which will account for the dynamic demand and supply management operations that are needed to run the system of MaaS as well as the complex daily data and information interactions between the models in the framework. The MaaS integrated controller will be based on combination of agent-based and event-based simulation techniques, complex mathematical programming and optimization methodologies.

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