MaaS modelling: a review of factors, customers' profiles, choices and business models

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Abstract

A mobility-as-a-service (MaaS) system is regarded as one of the emerging solutions that offer integrated, seamless, and flexible multi-modal mobility services as an alternative to privately owned mobility resources. MaaS is expected to change how users choose their modes of transport to reach their daily activities and how service providers generate profits, cooperate, and compete. To successfully deploy MaaS and achieve the intended goals, it is critical to develop feasible and sustainable models that capture the diverse needs of customers and the diverse and often competing objectives of service providers. This paper aims to provide a general modelling framework and a critical and descriptive analysis of the relevant literature relating to all main actors in the MaaS ecosystem and identify and discuss all factors that are considered relevant, focusing on the actors' decision-making processes and their correlations. This review shows the large variety and interaction of factors influencing MaaS adoption and their impact on forecasting MaaS appeal. It is also observed that current travel behaviour and multi-modal transport models are not fully capturing the diverse travel needs and choices of potential MaaS users. Recent advancements in agent-based simulation and discrete choice modelling offer potential solutions to address this gap, and future research should aim in that direction. Finally, the review analyses the interaction between MaaS actors, including customers, service providers, the government, and the MaaS Broker, highlighting the complexity of the modelling process comprising all actors of the MaaS ecosystem. Therefore, it is recommended to prioritise future research in exploring these areas.

1 Introduction

Since its introduction as a new transportation concept (Heikkilä, 2014; Hietanen, 2014), Mobility-as-a-Service (MaaS) has been widely studied among researchers and practitioners, becoming perhaps one of the most innovative and disruptive concepts introduced in the transportation sector in the last decade. MaaS is a complex ecosystem in which different actors with diverse purposes cooperate and compete to offer seamless multi-modal packages to customers through a subscription-based digital platform (Matyas & Kamargianni, 2017; Wong et al., 2018). In the MaaS ecosystem, different actors are involved, including policy regulators, mobility service providers (MSPs), customers, and the MaaS Integrator or Broker (Wong et al., 2018).

This seamless, multi-modal and personalised mobility concept can alter travellers' perceptions of mobility services, impact personal vehicle ownership and usage, and affect daily activity, mode and route choices. MaaS differs from traditional transportation modes because it is a multi-modal system with complex and dynamic interactions among actors driven by different and

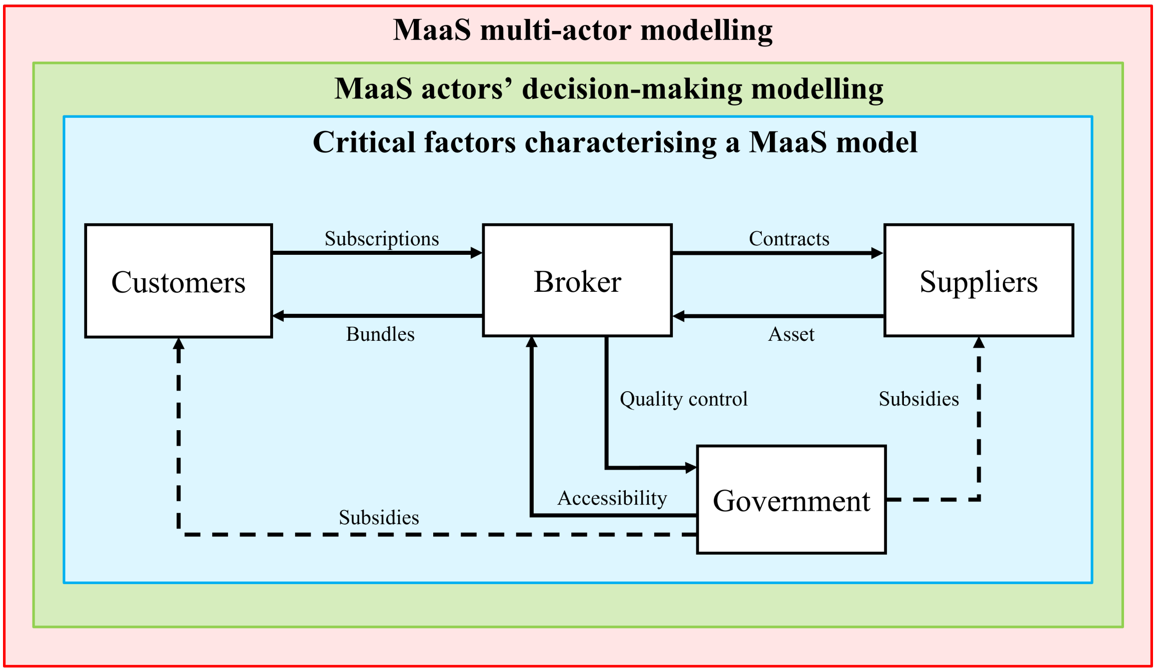

Figure 1: MaaS actors' roles and interaction (adapted from Wong et al. (2018))

often competing objectives. Conversely, such complexity is not fully encountered when a single transport service is modelled. Therefore, conventional transportation modelling and simulation approaches may not be ready to represent and quantify the multi-level impact of the MaaS system due to the lack of proper characterisation of the demand and supply interactions (Jittrapirom et al., 2017; Matyas & Kamargianni, 2018b). It is, hence, essential to develop a more suited modelling framework to represent the decision-making process at all levels and for all involved players and to develop operational planning strategies to perform MaaS execution. Although some studies have already provided insights into specific modelling requirements of the MaaS actors and their actions (Esztergár-Kiss et al., 2020; Rey-Moreno et al., 2023; Kriswardhana & Esztergár-Kiss, 2023; Hensher et al., 2023; Musolino et al., 2022), a general framework that incorporates all the components needed and their interaction to implement the MaaS system is currently missing. To the authors' knowledge, no general modelling framework can exhaustively model all the relevant characteristics. This study aims to fill this gap by reviewing and analysing the literature dealing with all characteristics necessary to model the relationships among the various actors in a MaaS ecosystem (see figure 1).

We conduct a critical and descriptive analysis of the literature considering the three aspects shown in Figures 1 and 2, namely (*i*) the critical factors essential to define a MaaS model, (*ii*) the different models for the decision-making processes of each actor, and (*iii*) the interactions between all actors. The present study aims to address and provide the basis to answer the following research questions and related sub-questions:

1. What are the critical factors that characterise a MaaS model?
    a. What are the customers' critical factors that impact MaaS adoption?
    b. What are the MaaS ecosystem related-factors that have an impact on MaaS appeal?

2. How to model the actors' decision-making process?
    a. What are the modelling characteristics needed to capture MaaS customer travel behaviour?
    b. How to model MaaS demand-supply interaction?

3. How to model the interactions among MaaS actors?
   a. What are the relevant modelling aspects to include to capture the interaction between all MaaS actors?
   b. How do we model the whole multimodal ecosystem, identify operating conditions, and include the institutional overlay for MaaS successful deployment?

The remainder of this paper is structured to address the above research questions in sequence. First, Section 2 explains the methodology used to select and review the state-of-the-art in the remainder of this section, Section 3 provides a classification and a general analysis of the critical factors determining customers' choices and profiles and relates individual characteristics with socio-demographic and other contextual variables, and finally connects these with MaaS-specific features, including technical design and market characteristics. Section 4 focuses on the MaaS actors' decision-making process, particularly on customers' choices (subscription choice, willingness to subscribe and to pay, mode choices) and on MSPs' strategic, tactical and operational decisions. Section 5 addresses the question related to multi-actor interaction, the design and assessment of different business models, and the modelling complexity of the two-sided market and the whole multi-modal ecosystem. Finally, Section6 provides conclusions and general recommendations for future research to fill the identified gaps and challenges.

2 Framework and literature review methodology

This study looks at the MaaS actors' interactions from a novel perspective by presenting the MaaS ecosystem in three different subsystems as proposed in Figures 1 and 2. Figure 1 is the starting point in which the three research domains are depicted, considering additional correlations between actors (dashed arrows), whereas Figure 2 represents the proposed framework of this paper in which the blue area (Critical factors characterising a MaaS model) includes all the relevant input to characterise a MaaS model. The green area (MaaS actors' decision-making modelling) defines the different models each actor uses to make decisions focusing on the customers. Finally, the red area (MaaS multi-actor modelling) aims to understand the interaction and strategies employed by all actors involved in MaaS, including the broker, the MSPs and the regulators.

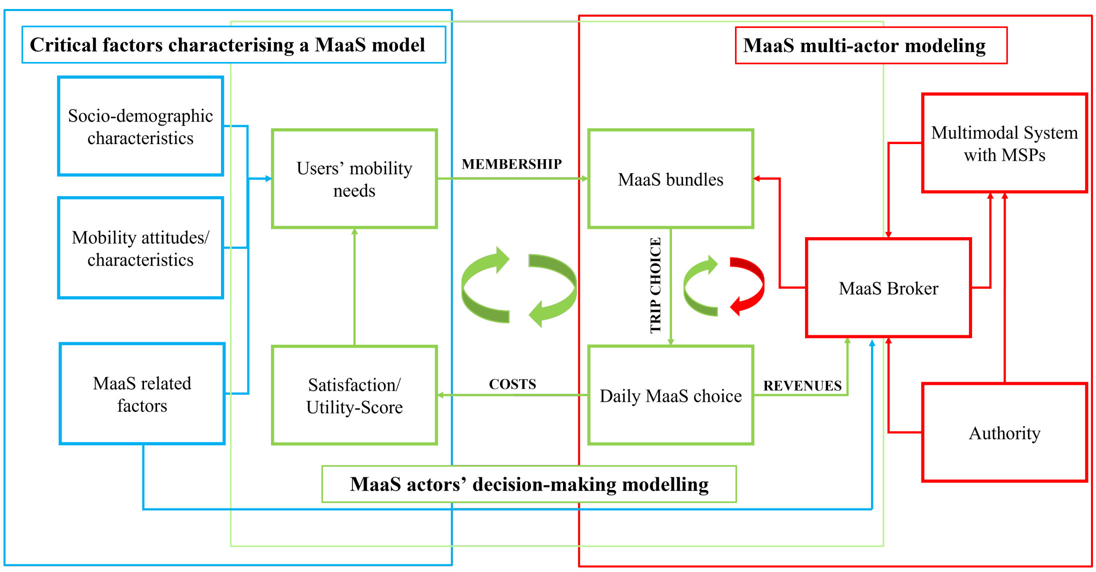

Figure 2: MaaS ecosystem modelling framework

A narrative review is conducted to present a comprehensive view of the literature on MaaS modelling and its components and to address the paper's formulated research questions.

2.1 Search strategy

Different databases have been used to find papers around the concept of MaaS modelling, employing ScienceDirect, Springer, Scopus, and Google Scholar sources. The papers in English published until the beginning of June 2023 were included in the search. Since MaaS is a novel concept that has been gradually considered in recent years, no timeline was considered when searching the papers. However, some broader terms were considered to help find the definitions and modelling details, i.e. multi-modal modelling, new mobility services, two-sided market, etc. Keywords including "Mobility-as-a-Service", "MaaS", and combinations of them with the Boolean operators (AND, OR, and NOT) were used to find the main publications. Then, frequently related keywords have been found in combination with MaaS, including "Agent-Based Models", "business models", "willingness to pay/subscribe", "mode choice", and "travel behaviour". For earlier papers, forward snowballing was used to find the citations; for newer papers, backward snowballing helped the authors find the citations in the paper (Van Wee & Banister, 2016).

Two hundred sixty papers were categorised according to their methodological approach and considered variables. The relevance of these papers was first evaluated through a preliminary screening to ensure that the studies encompassed relevant MaaS modelling aspects (such as transportation modes, user behaviour, service integration and policy and regulation). Subsequently, the retained papers were thoroughly analyzed through a full-text review. The included studies contain at least one of the following aspects: (*i*) Modelling of one or more MaaS subsystems; (*ii*) Mobility services or a subject in the field of mobility; (*iii*) Influencing factors of a MaaS model are studied.

Data extraction

The extracted data from the gathered papers include the study's characteristics, such as the year of publication, geographic location of the study (see Figure 3), methodology, selected indicators for MaaS modelling, the relationships of the indicators, goals, and main findings.

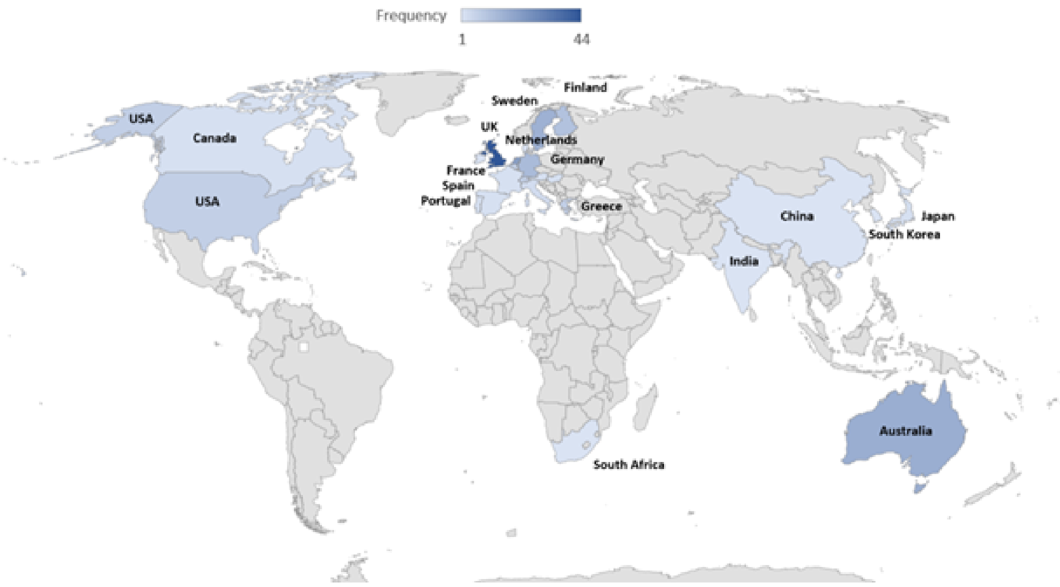

Figure 3: Distribution of MaaS studies around the world

Out of the MaaS-related articles, those that specifically focused on MaaS modelling, MaaS actors' interactions, analysis of the MaaS factors, multimodal transport network, equilibrium model and multi-sided market for MaaS were retained, resulting in a selection of 119 papers being included in the synthesis. In the next section, the most critical factors for defining and specifying a MaaS model will be discussed in detail.

3 Critical factors characterising a MaaS model

Determining the input data and variables is one of the modelling process's first and most important parts. The input of a MaaS model is the data that should be collected or measured from both the demand and supply sides. So, the data includes both user and provider's information (Rahbar et al., 2022). The data is then used to define the critical factors of a MaaS model. The factors are categorised into three groups in this work: (*i*) socio-economic characteristics, (*ii*) attitudes and habits of the travellers, and (*iii*) MaaS-related factors.

The definition and measurement of the included factors are analysed for each category. The reviewed literature reveals that the factors have effects on each other. The three main categories are shown in Figure 4 and are explained in this section. Blue arrows show the number of connections affecting the other category, and the pink ones show the connections affected by the other category. To illustrate the relationship between the parameters, a matrix approach is provided in Figure 5.

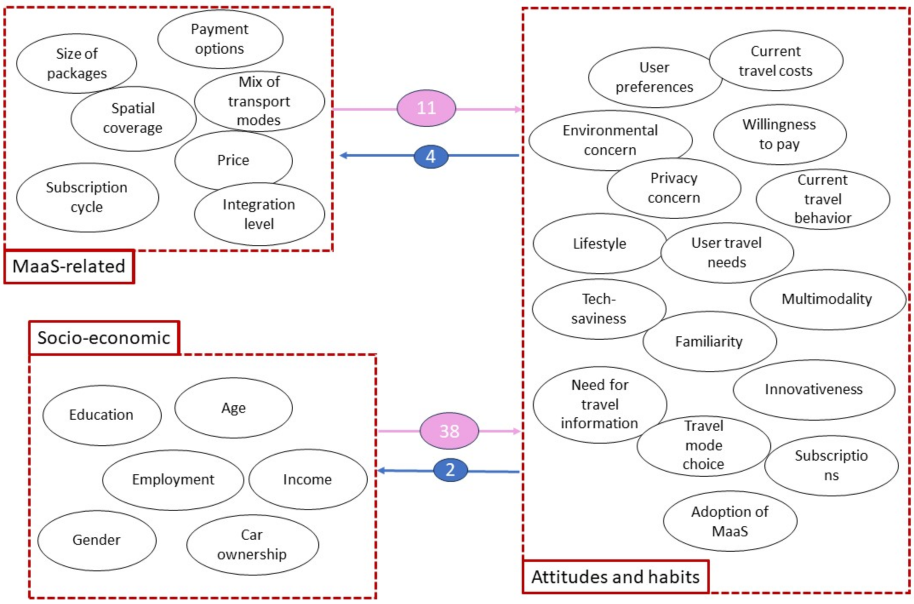

Figure 4: MaaS factors categories

3.1 Socio-economic factors

The main socio-economic factors analysed in the context of MaaS modelling include age, education level, gender, employment status, income, and car ownership (Tsouros et al., 2021; Matyas & Kamargianni, 2018a; Prillwitz et al., 2006; van 't Veer et al., 2023; Kriswardhana & Esztergár-Kiss, 2023). Among these factors, car ownership is a key factor expected to be influenced by MaaS adoption. This factor is strongly correlated with the other parameters, including age, gender, employment, education, and income (Prillwitz et al., 2006; Aguilar-Palacio et al., 2018; Avram & Popova, 2022; Dargay, 2001; De Gregorio & Lee, 2002; De Vos & Alemi, 2020; Nolan, 2010; Nutz & Lersch, 2021; Ong, 2002; Raphael & Rice, 2002; Rehman & Jamil, 2021; Somani, 2021; Thøgersen, 2018; Young & Caisey, 2010). It is revealed in the literature that gender, age, car ownership, and education of people affect employment (Nutz & Lersch, 2021; Raphael &

Rice, 2002; Somani, 2021); and employment, gender, and education affect income (De Gregorio & Lee, 2002; Nutz & Lersch, 2021).

Among the socio-economic factors, age is the most significant factor in MaaS models (Caiati et al., 2020a; Jang et al., 2020). Gender and income are the factors with higher coefficients after age (Jang et al., 2020). Moreover, income is more effective than car ownership and employment, and education is estimated to have the lowest effect (Caiati et al., 2020a; Tsouros et al., 2021).

3.2 Attitudes and habits of the travellers

General attitudinal aspects like privacy (Christiaanse, 2019; Cottrill, 2020), environmental concern (Bouscasse et al., 2018; Mehdizadeh Dastjerdi et al., 2019), lifestyle (Mehdizadeh Dastjerdi et al., 2019), health-related habits (Thøgersen, 2018; Duvigneaud et al., 2007; Johansson et al., 1999), innovativeness and tech-savviness (Zijlstra et al., 2020) are all critical factors to realise how concerned people are towards the adoption of MaaS.

Lifestyle is affected by age, gender, education, and income (Contoyannis & Jones, 2004; Fernandez et al., 2022; Luiu et al., 2018). Current travel behaviour of the users can be affected by different factors such as age, gender, income, education, lifestyle, and environmental concern (Thøgersen, 2018; Bouscasse et al., 2018; Delhomme & Gheorghiu, 2016; Neoh et al., 2017; Zarabi et al., 2019). Women and young people are usually more interested in public transportation than men (Broome et al., 2013). People with higher income and education usually choose private cars more than public transportation (Faza Fawzan Bastarianto, Muhammad Zudhy Irawan, Charisma Choudhury & Muthohar, 2019). User preferences and travel choices help to understand how likely travellers are to use a service. To measure these factors, people are asked about their preference to pay for different services (Matyas & Kamargianni, 2019; Vij et al., 2020; Kim et al., 2023b; Kriswardhana & Esztergár-Kiss, 2023).

Moreover, collecting users' travel choices helps to find the potential MaaS users as a function of some parameters such as car ownership, usage of the car and other modes (Mehdizadeh Dastjerdi et al., 2019; Zarabi et al., 2019; Vij et al., 2020), current transport costs (Vij et al., 2020), and mode choice under different conditions (weather, timing, traffic, costs) (Zarabi et al., 2019). The current travel costs can be asked directly or measured by estimating the costs according to the current travel modes and the level of satisfaction with their choices (Mehdizadeh Dastjerdi et al., 2019; Liljamo et al., 2020). Total Cost of Ownership (TCO) studies can help the customers to know the ownership cost of different services and compare it with MaaS (Liljamo et al., 2020).

Like any new service or product, MaaS designers and providers need to know people's willingness to pay and subscribe to the service (Matyas & Kamargianni, 2021). This important variable depends on how respondents are familiar with MaaS (Liljamo et al., 2020) and the types of modes and packages offered (Caiati et al., 2020a; Matyas & Kamargianni, 2019). Travellers subscribe to bundles according to their preferences for transportation modes, prices and subscription fees, subscription cycle, and socio-demographic profiles (Jang et al., 2020). Willingness to pay has been found to depend on socio-economic characteristics such as age, gender, employment, income, education, and current travel behaviour. This effect can be positive or negative, e.g., age has a diverse effect on the tendency to use MaaS packages, meaning that younger people are more eager to use them, and they should be considered an active target group (Zijlstra et al., 2020; Vij et al., 2020; Matyas & Kamargianni, 2021; Casadó et al., 2020; Matyas, 2020). The literature also mentions that younger users who work full-time are more interested in paying for MaaS than older retired customers (Vij et al., 2020).

Willingness to subscribe to MaaS also depends on socio-economic factors such as income, age, gender, and employment (Caiati et al., 2020a; Hörcher & Graham, 2020). Price, payment options, environmental concerns, subscription cycle, travel needs, user preferences, and current travel behaviour also affect the preference of travellers to subscribe (Matyas & Kamargianni, 2019; Caiati et al., 2020a; Kamargianni & Matyas, 2017).

Car ownership is another factor that affects subscriptions (Caiati et al., 2020a). The literature also mentions that increases in MaaS subscriptions will affect and, particularly, reduce car ownership and car use (Hensher et al., 2021; Hörcher & Graham, 2020). Although special prices and discounts can be offered in the packages, long-term subscriptions and monthly payments might be an obstacle for some users, especially those who have recently joined the new mobility users. Thus, initially, limited bundles and pay-as-you-go offers might be more acceptable for the users (Ho et al., 2021).

Recent studies reveal that the early adopters of MaaS have some specific characteristics, such as being innovative, open to new technologies, feeling a need to travel information, and having a multi-modal mindset (Zijlstra et al., 2020). Multimodality is one of the important factors in MaaS models, and it is affected by the mode choice of the users. It is observed in the literature that customers' age and gender affect their innovativeness and interest in new technologies (Kim et al., 2011; Wei, 2005).

3.3 MaaS-related factors

Services-related factors are clearly affecting the adoption of MaaS. For instance, because users have more than one payment option, including pay-as-you-go and monthly packages, it is important to consider payment options as a critical factor (Ho et al., 2018, 2021; Kamargianni & Goulding, 2018). Price is one of the other service attributes that should be investigated, as the decision of the users to adopt MaaS depends on the price of the packages (Caiati et al., 2020a).

MaaS packages are offered in different sizes, from limited ones, including public transport and shared modes like bike sharing, to large ones with more transport modes (Matyas & Kamargianni, 2021; Madani et al., 2022). The size of bundles is also impacting MaaS adoption, with students being mostly interested in small packages like public transport and bike-sharing, and the group with high income and a high level of education seem more interested in larger packages (Matyas & Kamargianni, 2021).

Users subscribe to MaaS packages in a long or short process cycle. This is measured by understanding which is simpler for the travellers and whether they are familiar enough with MaaS packages to subscribe for a long period (Ho et al., 2021).

The mix of transport modes in the bundle also plays a role in travellers' decisions, with Public Transport being considered the backbone of the whole system (Matyas & Kamargianni, 2019; Kriswardhana & Esztergár-Kiss, 2023).

To compete with recent transportation services, especially with private cars, a high-density transport network is necessary to cover both rural and urban areas with 24-hour coverage similar to private cars. So, spatial and temporal coverage play important roles in MaaS models (Kamargianni & Goulding, 2018). The spatial coverage can be in traffic or urban zones. To measure this factor, it is necessary to know if the cards or tickets of a mode are available and active in an area (Ho et al., 2021).

MaaS aims to improve the level of integration to raise social, environmental, and economic benefits (Lyons et al., 2019). This integration involves mobility services, transport modes, sectors, operators, and institutions. It has different levels, including no integration, basic integration, limited integration, partial integration, full integration under certain conditions, and full integration under all conditions (Lyons et al., 2019; Kamargianni et al., 2016; Preston, 2012). It is confirmed in the literature that booking, ticketing, and planning are crucial in a MaaS platform (Athanasopoulou et al., 2022). Therefore, the best is to have the highest possible level of integration.

The factors considered in the literature in MaaS-related studies are categorized in Table 1. The numbers 1, 2, and 3 in the category column in Table 1 refer to socio-economic, attitudes and habits, and MaaS-related categories, respectively.

Figure 5 depicts how factors affect each other to comprehend the connections between the variables explored through an anti-symmetric matrix. Blue and pink squares show the colour of

Table 1: MaaS influencing factors in the literature

Authors, year	Main variables	Category
Cottrill (2020)	Privacy concern	2
Thøgersen (2018) Kim & Rasouli (2022)	Lifestyle	2
Bouscasse et al. (2018)	Environmental concern	2
Lyons et al. (2019) Preston (2012) Kamargianni et al. (2016)	Level of integration	3
Hensher et al. (2021)	User preferences	2
Macedo et al. (2022)	Payment, Customisation	3
Matyas & Kamargianni (2019)	User preferences, Subscriptions	2
Kriswardhana & Esztergár-Kiss (2023)	Socio-demographic and technical factors	1,3
Duan et al. (2022)	Behavioral and Socio-economic factors	2,3
Ho et al. (2021)	Subscription cycle, Spatial coverage	3
Matyas & Kamargianni (2021)	Willingness to pay, Size of packages	2,3
Kamargianni & Goulding (2018)	Payment options, Employment,Spatial coverage	1,3
Vij et al. (2020)	User preferences, Current travel behaviour, Current transport costs	2
Zarabi et al. (2019)	Current travel behaviour, Travel mode choice in different conditions, Current travel costs	2
Liljamo et al. (2020)	Current travel costs, Willingness to pay, Familiarity	2
Tsouros et al. (2021)	Age, Education, Employment, Income	1
Zijlstra et al. (2020)	Innovativeness, Tech-savviness, Need for travel information, Multimodal mindset	2
Jang et al. (2020)	Subscriptions, User preferences, Price, Subscription cycle, Sociodemographic profiles	1,2,3
Mehdizadeh Dastjerdi et al. (2019)	Privacy concern, Current travel behaviour, Current travel costs, User travel needs, Environmental concern	2
Caiati et al. (2020a)	Subscription, Price, Subscription cycle, Adoption, Age, Income, Car ownership	1,3
Esztergár-Kiss & Kerényi (2020)	modal split	2

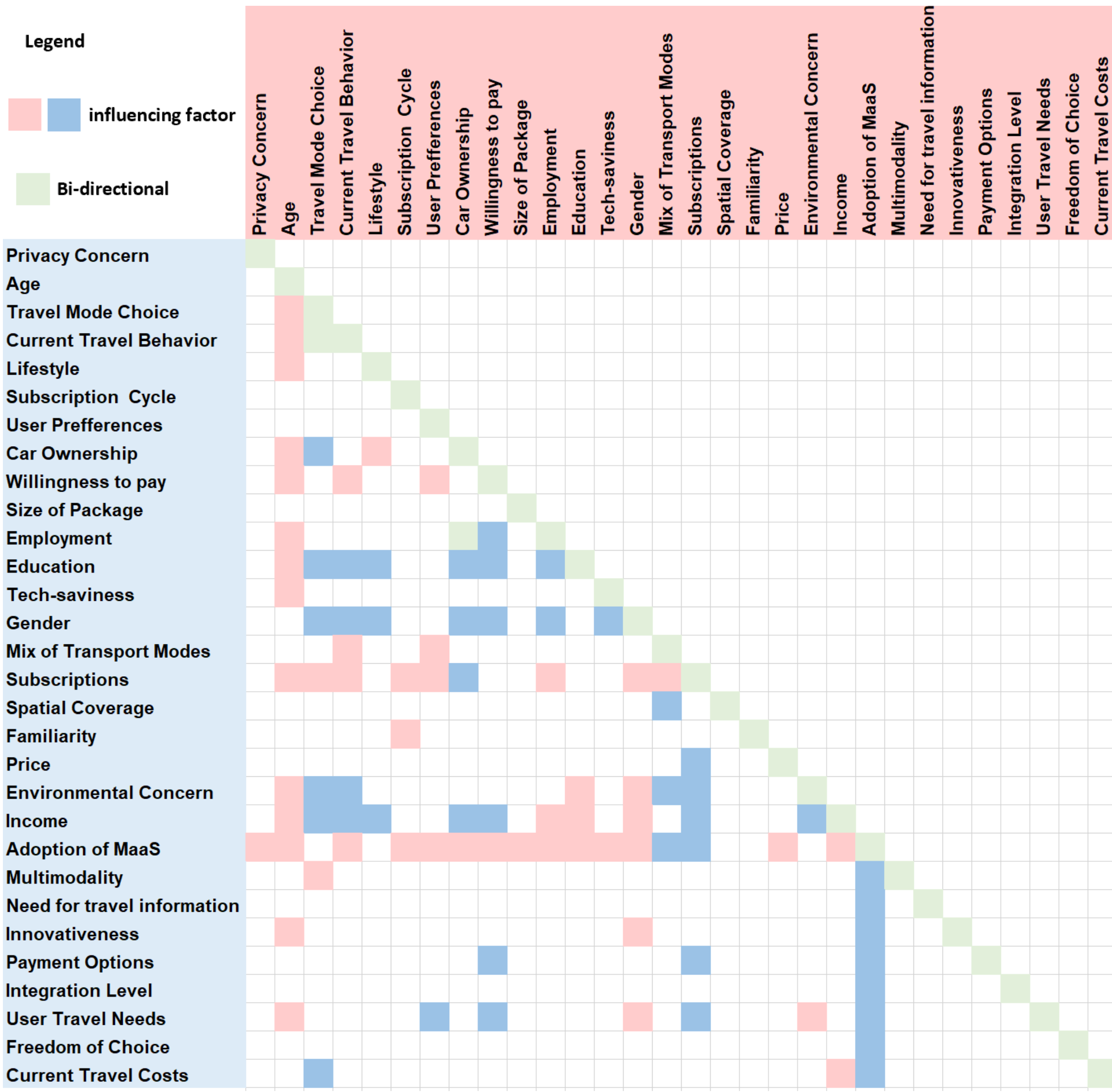

Figure 5: Visualisation of the interactions of the factors

the influencing factor in that row or column. In contrast, the green colour shows that there is a bi-directional effect. Although many of the factors interact, it is difficult to understand all of the connections that may impact forecasting MaaS adoption.

4 MaaS actors' decision-making modelling

This section discusses the current MaaS decision-making models for MaaS actors, developed based on the critical factors described in the previous section.

With MaaS models, we refer to analytic, simulation-based, or data-driven approaches developed to estimate and predict the decision-making process driving the choices of all the MaaS actors. A substantial portion of the literature in this area focuses on the decision-making process of customers, specifically on the two points listed below:

1. MaaS subscription choice models. This is a mid-term decision-making process since it involves choosing, e.g. a monthly subscription, which determines and, to some extent, limits the possibility of using mobility services on a daily or weekly horizon (e.g., a limited number of hours for renting a shared vehicle included in the MaaS package to be used within the subscription month);

2. MaaS mode choice models, which aim to explain or forecast one or more daily travel decisions, i.e. which sequence of modes, including but not limited to just MaaS services, should be selected by the users to fulfil their planned daily activities taking into account the characteristics of the MaaS package (e.g. limited number of trips or access time for a service).

MaaS customers' models involve tightly connected strategic, long-term, and tactical pre-trip decisions. This section reviews the existing literature on such models, the travel demand resulting from individual choices, and their interactions with supply characteristics. It leaves decision-making models of other relevant actors (service providers, authorities) to the following section as part of the multi-actors modelling section.

4.1 MaaS demand models

The MaaS modelling paradigm intends to capture a wide range of travel demands, including different user profiles, by capturing their heterogeneous mobility needs (Cisterna et al., 2023). Given the wide range of mobility needs that MaaS bundles should meet, it is crucial to characterise MaaS demand in terms of the spatial and temporal distribution of both users' mobility requirements and mobility options offered by MaaS (Matyas & Kamargianni, 2021; Wong et al., 2020). Thus, customers' travel patterns require accessible and flexible modes of transportation. If services are unavailable or of poor quality, it may impact customer decisions and lead to subscription reconsideration.

Demand and bundle design are crucial factors in a MaaS decision model and are interrelated (Sochor et al., 2016). Understanding how users' travel needs and mobility services availability interact within the bundle is essential. MaaS models should account for changing demands on different days, such as weekends versus weekdays. To capture diverse mobility requirements within daily and multi-day trips, a long-term perspective is necessary for the MaaS decision-making model (Reck et al., 2020).

MaaS demand emerges from individuals' subscription and mode choices. To understand mode preferences, trip chains must be described at the individual level, and services must be modelled at the vehicle level to assess resource utilisation. MaaS packages include new mobility services (e.g. on-demand or autonomous), so capacity and availability must be accurately represented. Bundle design can incorporate different schemes to accommodate diverse mobility needs, such as time-limited access or discounted costs per trip (Hensher et al., 2021; Tsouros et al., 2021).

In this context, the typical approaches are unsuitable to model MaaS demand. The trip-based model cannot represent users' trip chain and mode choice decisions. At the same time, a tour-based framework might be incapable of modelling the variety of users' activities over different days (Hasnine & Nurul Habib, 2021). Additionally, one of the most significant barriers to characterising, forecasting, and optimising MaaS demand is a lack of real data to support it, as the MaaS system is not yet available in the market or has not been implemented long enough to observe its long-term impact on transport and mobility patterns. For this reason, the main approaches in the literature to modelling the MaaS potential demand rely on either stated-revealed preference surveys or data and observations collected during pilot projects.

Stated-preference survey-based approaches

In survey-based approaches, participants share their mobility habits and socio-demographic characteristics with the modellers. Successively, the interviewees are asked to state their preferences in hypothetical scenarios in which different MaaS bundle options are proposed. These scenarios include a selection of available mobility services and costs, which the analyst can set, or the participants can choose among a set of predefined options (e.g., Matyas & Kamargianni (2017); Tsouros et al. (2021); Caiati et al. (2020b); Ho et al. (2019)). Besides MaaS scenarios, the participants' current travel choices are also collected to relate them to the interviewees' travel habits.

The survey approach is typically adopted to generate data and validate and calibrate discrete choice models, which are meant to estimate the individuals' MaaS decision-making process. In the literature, few studies focused on estimating models for understanding users' willingness to subscribe to MaaS and their preferences for bundle types, including additional features and a set of individual characteristics, such as transferability, vouchers or designing unlimited usage of specific services within the bundle ((Tsouros et al., 2021; Matyas & Kamargianni, 2019; Ho et al., 2018; Caiati et al., 2020b; Ho et al., 2019; Krauss et al., 2023)). Guidon et al. (2020) conducted a discrete choice experiment to study consumers' cost evaluation for single or bundled services. By introducing in the survey further questions concerning participants' perceptions or behavioural attitudes or intentions, they investigated bundles' impact on users' willingness to subscribe to MaaS ((Zijlstra et al., 2020; Vij et al., 2020; Alonso-González et al., 2020; Feneri et al., 2020; Fioreze et al., 2019; Kim et al., 2021; Polydoropoulou et al., 2020b; Schikofsky et al., 2020; Ye et al., 2020; Kim & Rasouli, 2022)).

Further characterisations of end-user profiles were proposed by employing a cluster analysis process involving attitudinal factors, such as attitude towards car usage or public transport, towards shared mobility services, or technologies ((Vij et al., 2020; Liljamo et al., 2020; Matyas & Kamargianni, 2021; Alonso-González et al., 2020; Feneri et al., 2020; Lopez-Carreiro et al., 2021)). Conversely, estimation of willingness to subscribe to MaaS within specific target groups (e.g., aged people) has been performed (Mulley et al., 2020; Caiati et al., 2020a). However, due to some simplifications of discrete choice models, the representation of users' potential travel decisions might not be fully realistic. For instance, a multinomial logit model relies on the independence of irrelevant alternatives (IIA) and assumes that the alternative with the highest utility is more likely to be chosen by the respondent without considering the interaction among sequential daily choices ((Tsouros et al., 2021; Ho et al., 2018, 2019; Mulley et al., 2020; Narayanan & Antoniou, 2023)). Moreover, multinomial logit does not fully consider the variety of travel needs among users. Hence, it is limited in capturing users' heterogeneity, which is essential to estimating MaaS potential demand (Tsouros et al., 2021). To overcome those limitations, several studies in the literature employ a mixed logit approach, in which the correlations in unobserved factors and different tastes across interviewees are incorporated (e.g. Matyas & Kamargianni (2019); Caiati et al. (2020b); Guidon et al. (2020); Alonso-González et al. (2020); Kim et al. (2023a); van't Veer et al. (2023)). Besides, the inclusion of latent variables in a mixed logit model has been explored through hybrid modelling estimation, in which hidden variables representing attitudes or perceptions of the users are included in the survey. These latent variables try to explain the travel behaviour through specific attitudinal answers and are successively measured by indicators in the model estimation (Ben-Akiva et al., 2002).

Revealed-preference pilot-based approaches

An alternative approach to model the MaaS potential demand and overcome the issues faced by applying a discrete choice model consists of running a pilot project (Alonso-González et al., 2020). Pilots aim to gather all information through early experience with the new services. This approach allows users to test the MaaS package type and its potential members at specific times and locations. It also helps analysts give observations by investigating the impact of specific MaaS bundle solutions in reality. Participants are recruited before running the pilot and selected to capture the most relevant aspects of MaaS demand in diverse contexts.

Several MaaS trials have been run around the world using different platforms, for instance, UbiGo in Sweden (Karlsson et al., 2016; Sochor et al., 2018), Tripi in Australia (Hensher et al., 2021), Touring in Belgium (Storme et al., 2019), and only in the last half-decade commercial operating organisations are providing MaaS as real services (for instance, Whim in Finland and the Netherlands[1], Mobil-Flat in Germany[2], Yumuv in Switzerland[3], Gaiyo in the Netherlands[4], MyCorridor Salzburg-Athens and Korinthos-Amsterdam[5], Smile in Austria[6], and MyCicero in Italy[7]).

Generally, in the trials, revealed preference studies are employed to validate and evaluate the potential of MaaS bundles and the users' travel behaviour (Sochor et al., 2016; Karlsson et al., 2016; Strömberg et al., 2018; Musolino et al., 2023). For instance, Storme et al. (2019) evaluated car owners' readiness to shift from a private car to a MaaS bundle through questionnaires. Strömberg et al. (2018) categorised different user groups by applying a cluster analysis. Within the same pilot project, Karlsson et al. (2016) analysed in-depth information on the reasoning behind participants' opinions and experiences using the MaaS service. To the best of the authors' knowledge, a first joint approach using a discrete choice model and data from a pilot has been employed by Hensher et al. (2021) and Ho et al. (2021). During this pilot, diverse subscription plans have been incrementally presented to the participants due to a data analysis process over the trial period. Hensher et al. (2021) investigated the potential influences of the choice between subscribing to a monthly MaaS bundle and the pay-as-you-go (PAYG) option and how that impacts the total monthly car kilometres. Ho et al. (2021) estimated a choice model using revealed-stated preferences to assess the interest in MaaS subscription bundles compared to PAYG. Table 2 displays the summary of all papers above-discussed by methods and their focus for both approaches (stated-preference survey, revealed-preference pilot-based).

Table 2: Summary of methods, authors and their focus for MaaS demand modelling

Method	**Authors, year**	**Focus**
	SURVEYS	
Regression analysis	Fioreze et al. (2019)	Attitude among residents towards the introduction of MaaS
	Liljamo et al. (2020)	Estimating the current mobility costs of the respondents and relating their willingness to pay (WTP) for MaaS to their mobility costs
Heteroscedastic non-linear random parameter Multinomial logit	Ho et al. (2018)	Understanding what types of MaaS subscription plans might appeal to potential users
	Ho et al. (2019)	Different business bundle models and their appeals
Error logit component	Feneri et al. (2020)	Understanding the model shift as a result of the availability of MaaS
	Krauss et al. (2023)	Transport supply and mobility behaviour on preferences for MaaS bundles in multiple cities
Multinomial logit	Tsouros et al. (2021)	Exploring demand and WTP for MaaS
	Narayanan & Antoniou (2023)	The development of a joint mode choice model for bike-sharing, car-sharing and ride-hailing services
	Mulley et al. (2020)	The WTP for bundles of mobility services

Continued on next page

[1]https://whimapp.com
[2]https://mobility-talk.com/mobil-flat-in-augsburg-einmal-zahlen-alles-fahren
[3]https://yumuv.ch/en
[4]https://gaiyo.com/?lang=en
[5]http://www.mycorridor.eu
[6]https://smartcity.wien.gv.at/en/smile-2/
[7]http://www.mycicero.eu

Table 2 – continued from previous page

Method	Authors, year	Focus
Mixed logit	Caiati et al. (2020b)	Formulating and estimating a discrete choice model for MaaS adoption decision
	Kim et al. (2023a)	Understanding relationships of the tourist preference for tourism travel alternatives represented as MaaS
	Matyas & Kamargianni (2018b)	Understanding potential modes and features to be included in the MaaS plan and the WTP for these features
	Guidon et al. (2020)	Analysing the difference between bundle and sum-of-parts WTP to determine bundling valuation
	Matyas & Kamargianni (2019)	Identifying individuals' preferences for the modes in the plans
	Caiati et al. (2020a)	Explore potential MaaS adoption considering age groups and life stages of potential users
Latent class	Alonso-González et al. (2020)	Identifying factors relevant for MaaS adoption
	van't Veer et al. (2023)	Providing insights into which factors influence the intention to use MaaS among private vehicle owners
	Kim & Rasouli (2022)	Understanding how people's lifestyle associated to WTP
Hybrid choice model parts	Polydoropoulou et al. (2020b)	Individualising preferences for MaaS
	Matyas & Kamargianni (2021)	Examining individual preferences for MaaS packages
	Kim et al. (2021)	Identifying users' preference for intermodal options under MaaS adoption
	Schikofsky et al. (2020)	Understanding motivational mechanisms behind the intention to adopt MaaS
	Lopez-Carreiro et al. (2021)	Identifying a set of attitudinal and personality factors relevant for MaaS adoption
	Vij et al. (2020)	Understanding consumer demand and willingness to pay for MaaS
PILOTS		
Statistic analysis	Storme et al. (2019)	Exploring car usage reduction in return for a monthly mobility budget, which they could spend on MaaS services
	Musolino et al. (2023)	Capturing the main behaviour variables of MaaS transport users
"before", "during", "after" questionnaires	Sochor et al. (2016)	Insights from a six-month field operational test
	Strömberg et al. (2018)	Analysing who is the potential MaaS customer
	Karlsson et al. (2016)	Insights from the trial and evaluation of an example of MaaS
The binary choice model	Hensher et al. (2021)	Investigating the potential for changes in monthly car use in the presence of a MaaS program
Mixed logit with correlated random parameters	Ho et al. (2021)	Assessing the interest in MaaS subscription bundles compared to PAYG

Although the reported stated-revealed surveys and pilot projects provided fundamental insights into the MaaS customers' decision-making process and have advanced the understanding of the MaaS users' choices, both approaches are limited in terms of the general representation of mobility requirements and activities performed by participants. The survey results might not cover the whole population heterogeneity, as pointed out by Fioreze et al. (2019); Ho et al. (2018); Lopez-Carreiro et al. (2021). The pilot-sample size is often too small to capture the MaaS demand variety and analyse MaaS potential users' travel behaviour, as underlined by Hensher et al. (2021); Sochor et al. (2016); Storme et al. (2019).

The pre-selection of pilot participants guarantees a limited observation of the MaaS making-decision process. Moreover, attitudes employed to analyse users' willingness to subscribe during the survey campaign might change due to different experiences, perspectives, networks and new assessments (Alonso-González et al., 2020). Although the MaaS system intends to capture the variation in travel demand by promoting multimodality, the survey strategy does not allow a real experience of the new services, even proposing realistic multi-modal MaaS bundle scenarios. The interviewees' choice is the outcome of previous experiences that do not comprise a multi-modal journey under one subscription fee but rather a trip chain based on time-linked cost. Therefore, the users choose a scenario that might not represent their future real mobility choice. Currently, there is a lack of sophisticated models that can accurately capture the diverse mobility needs of users and the potential services offered by MaaS. However, recent research has begun exploring agent-based simulation approaches to address this limitation and bridge the gap (Cisterna et al., 2023; Kucharski & Cats, 2022).

4.2 Modelling the MaaS demand-supply interaction

The above-described MaaS choice models allow quantifying the importance of the factors described in section 3 in the users' decision-making process. Still, they cannot fully capture the interaction between users' preferences and the characteristics and dynamics of the supply system. Hence, to capture the emerging mobility patterns and the demand-supply interactions, a more advanced method is needed which captures the users' mobility needs (i.e., which modes and MaaS packages would the users need to reach their planned locations and activities) and represents users' dynamic response to the performance of the supply system.

In this respect, agent-based modelling (ABM) allows the simulation of each agent's (or user's) behaviour in terms of their activity and travel options at a microscopic level. Furthermore, the agent-based approach enables agents to display sophisticated behaviour, adapt, and learn from experience through decision-making processes that strive to reduce their travel expenses (Bonabeau, 2002). Travel costs can be calculated by replicating mobility decisions and the spatial and temporal characteristics of the supply in terms of schedules and capacities as they are made in the actual world (Ciari et al., 2008). Ultimately, the model enables the analysis of aggregated behaviour and understanding of population trends through the microscopic characterisation of each single agent (Bonabeau, 2002).

Few authors have employed the ABM approach to model the MaaS decision-making process. For instance, the studies by Cisterna et al. (2022) simulated a MaaS service by endogenising the MaaS subscription and mode choices within the agent choice set to allow a virtual experience of the service in terms of subscription fee and capacity constraints. Each agent in the ABM perceives the trade-off between the MaaS subscription fees and time-linked mobility service costs. Finally, comparing the outcomes with a scenario in which MaaS was not a mobility option, the authors investigated the impact of MaaS bundle price on MaaS demand regarding customers' travel attributes. Kucharski & Cats (2022), instead proposed the MaaSSim agent-based simulator; this model can represent agents' taste variations (heterogeneity), their previous experiences (learning) and available supply information (system control). Within the simulation, agents are individual decision-makers who might be able to reject or accept a specific incoming ride proposed by another type of agent, the drivers. Vice versa, the drivers may opt out of the system or reject incoming travel requests, whereas an intermediate agent, the platform, matches demand with supply to achieve equilibrium. In Cisterna et al. (2023) study, car policy as the total cost of ownership (TCO) is embedded in the ABM to identify its impact on MaaS demand. Varying the TCO among diverse scenarios and simulating a specific type of MaaS plan giving unlimited access to the services, the authors identify two potential customers' travel behaviours regarding modal shift and travel characteristics.

While some models presented in the literature have started filling the gap in knowledge of Maas decision-making modelling, different challenges remain to be addressed. A more sophisticated model is needed to capture the dynamic response between demand and supply, optimise MaaS bundles regarding mobility services and their service characteristics, and provide competitive subscription fees. Moreover, the MaaS choice might not solely depend on the single user's choice but on a set of travel requirements, which may depend, for instance, on family members. Hence, a model that can represent the influence of other users' choices on an individual mobility decision is still missing. MaaS systems might also be employed in different domains, such as for private companies and municipalities. Therefore, a more general and flexible MaaS decision-making model is needed to forecast the MaaS demand within diverse backgrounds. Additionally, interactions with different actors need to be addressed in a MaaS decision-making model; for instance, the possibility of applying subsidies such as car policies to encourage users' modal shift toward MaaS development or a specific allowance for selected mobility services within bundles.

5 MaaS multi-actor modelling

A successful MaaS implementation relies on understanding the interaction and decision-making strategies of all actors in the MaaS ecosystem, including the Broker, the Mobility Service Providers (MSPs), and the policymakers (road authorities, government). The policymakers are responsible for the availability of services, for offering the supply capacity and organisations, and for defining policies for supporting the business viability of MaaS systems (e.g., via subsidies, restricting access to competing alternatives such as private cars, or inversely granting accesses or privileges such as dedicated and exclusive parking spots). Modelling the collaboration and inclusion of a large share of transport operators offering their services in an area where a local authority is regulating is essential to assess the feasibility of implementing a specific MaaS business model in a given context.

Aspects concerning the relevance of suppliers joining MaaS (Polydoropoulou et al., 2020a), the inclusion and key role of Public Transport in the ecosystem (König et al., 2016), and direct collaboration with the government (Wong & Hensher, 2021) have been analysed in the literature. Nevertheless, a model that captures the complex interaction between services and actors (e.g., comparing competition vs cooperation strategies) has not yet been introduced. For this reason, in this section, we analyse the literature focused on MSPs and the role of the government to understand the next fundamental steps to assess this system entirely, as depicted in Figure 1. To understand how to model this multi-actor and multi-modal system, we focus on (i) the different types of business models that can be developed to define the relationship between MaaS Broker and MSPs, (ii) how to develop MaaS as a platform-based system, and (iii) how to include the government and the users' choices in a multi-modal context.

5.1 MaaS Business Models

In the MaaS Ecosystem, each actor involved usually has a distinct business model based on the "product" they are selling. By business model, we intend a specific modelling aspect that defines the service actors' strategies, i.e. a business model represents how a company creates customer value (Eckhardt et al., 2017). When joining a MaaS system, companies must adapt and change their Business Model (BM) to have a profitable service (Polydoropoulou et al., 2020a). Understanding this adaptation, how to maintain their identity inside the MaaS market, and whether it is possible to define a general BM valid for different MSPs and scalable to multiple locations is still unclear.

One of the main aspects that must be considered that affects the definition of a general BM is the interaction between MSPs and the MaaS Broker. The MaaS Broker is the central actor operating between MSPs and users (Kamargianni & Matyas, 2017). To understand the role of this new figure, Eckhardt et al. (2017) studied different pilots and mobile applications developed in Europe. Three MaaS Broker models are identified: commercial, public, or public-private partnership (PPP). It's important to note that all mobility services in a MaaS system should be fully integrated, including ticketing, payment, planning, booking, mobility packages, customer support, and regulation. These services should be accessible through a single mobile application.

Examples of such applications have been mentioned in Section 3.

An essential task of the MaaS Broker is to gather the relevant MSPs from the area under analysis and create packages based on the users' needs. This actor needs to define the right business contracts with MSPs to build these packages. Following Eckhardt et al. (2017), the service agreements could include re-sold services when there is a list of fares or a percentage of fixed reduction; negotiated services, instead, are considered when the fares are based on bilateral agreements. Some practical examples can be found in existing mobile applications. MaaS Global, the developer of the Whim App[8], purchases mobility services in advance, such as bus, taxi, and bike rides, based on users' monthly trips and profiles. These rides are then combined into packages and sold for profit. In Berlin, through the Jelbi App[9], Berliner Verkehrsbetriebe (BVC) has the task of handling contracts with MSPs to have a high level of integration for users that can pay for each mobility service directly on the app. The Trafi company handles the integration. Trafi and BVG are not involved in the payment process, they provide only the integration in the platform. The type of agreement adopted is based on the area analysed, regulations, and the number of MSPs willing to participate. In this context, a MaaS model must be general enough to capture the possible business agreements between MSPs and the MaaS Broker.

Recently, van den Berg et al. (2022) developed an economic framework in which mobility services are studied through a supply chain structure. The authors investigated various business models in a competitive transportation market involving two MSPs, with and without a MaaS platform. While this approach has certain limitations when applied to large-scale and complex networks, we believe that these economic studies should be embraced to conduct ex-ante analyses of different business scenarios. Specifically, an economic framework that predicts potential outcomes based on adopting various business strategies between MSPs and the MaaS Broker could guide MSPs in choosing the most profitable option.

5.2 Modelling the two-Sided market

As pointed out by Calderón & Miller (2020), some authors have proposed the two-sided market (or multi-sided platform) concept to model the interaction between users and MSPs in a MaaS context. Using this approach, a platform (or several) supports the interaction between different sides and, unlike usual transportation models, it has to be attractive to MSPs and users (Meurs & Timmermans, 2017). In their discussion paper, Meurs & Timmermans (2017) define important factors when modelling MaaS as a multi-sided platform. The demand can choose to use the MaaS application, where several services are offered, or purchase each mobility service separately. Utility functions can be defined for each service, considering classical mode choice characteristics related to the mobility service and the users and new aspects connected to uncertainty and trust. MSPs, instead, might participate in the platform only if the service becomes profitable. Each MSP seeks to maximise their profit function, which depends on "the number of users of the services, price/fares of the trips, the marginal costs of the trips per traveller as well as fixed costs of the service provider and costs of the platform". The authors believe that this profit depends on three main factors: (*i*) demand, (*ii*) costs, and (*iii*) competition strategy. It seems extremely important to quantify the impact of competition between different MSPs joining the MaaS platform to understand their willingness to participate. In this context, the authors suggest that game theory be used to study the behaviour of all MSPs at equilibrium. Albeit the interesting suggestions, the work of Meurs & Timmermans (2017) does not include a precise modelling solution.

A more practical approach, developed by Djavadian & Chow (2017a), proposes an agent-based day-to-day adjustment process considering MaaS as a two-sided transport market. In this model, flexible transport services (FTSs), such as ridesharing, car-sharing, and taxis, are considered first/last mile options to complete a trip with transit services. An FTS is modelled

[8] https://whimapp.com

[9] https://www.jelbi.de/en/home/

as a seller in the two-sided market; the defined environment represents the platform, and users are the buyers of the service. The authors adjust passenger and vehicle fleets as an extension of Djavadian & Chow (2017b). In this way, the FTS operating policy is also adjusted. Although different drivers of a specific FST are considered, this model assumes that travellers use them as a first/last mile connection while travelling the main distance with transit services. Most of the concepts that characterise the MaaS concept are not included. Specifically, we believe that a representative model of MaaS should: (*i*) include a multi-modal system with all modes of transport; (*ii*) encode directly in the model the concept of mobility subscription to capture cooperation between MSPs; (*iii*) include a multi-actor system able to analyse the impact of Government' policies on different MSPs' strategies subject to users' heterogeneous modal choices inside a MaaS platform.

5.3 Multi-modal multi-actor system

Classical transportation approaches must be extended to model a multi-modal and multi-actor system like MaaS. Following this purpose, in their literature review, Pham et al. (2021) seek to identify the accessibility indicators that can influence the interaction between the different MaaS actors to develop a conceptual framework to model them. The main findings of this study underline the presence of several gaps in the transportation literature. In particular, current models do not consider (*i*) psychological indicators to quantify demand-supply interaction; (*ii*) dynamic pricing; (*iii*) monthly service users to optimise the offer; (*iv*) the efficiency of the entire transport system; and (*v*) MSPs' point of view when defining packages and mobility options based on users' preferences and available services.

A first step towards a more comprehensive modelling framework has been proposed by Kamargianni et al. (2019), which is divided into different components to take into account how to structure the business ecosystem, how to replicate the functionalities of the MaaS platform and how to model the response of the demand through an agent-based modelling a multi-modal network. This general framework is combined with the simulation model SimMobility[10]. This agent-based, activity-based, multi-modal simulation platform models individual travel decision-making and transportation systems operations at different time scales. The cited work, however, proposes a framework without showing any application in a real scenario. Furthermore, the role of the government or the local authorities does not appear crucial for developing the MaaS system.

The government, instead, plays an important role in the MaaS system since it can introduce subsidies and taxation policies, define the role and centrality of PT in the MaaS system and favour the MaaS market and business viability. Moreover, Pagoni et al. (2022) pointed out the importance of improving and defining new regulations at a European and national level to help the development of MaaS in Europe. Finally, all private service providers are important to let MaaS become a valid alternative to private, single-occupancy car usage (Karlsson et al., 2020). An interesting work by Dandl et al. (2021) defines a tri-level model, which considers the government at the highest level in defining regulations, transit service designs, and plans to maximise social welfare. In the second layer, a single MSP tries to maximise profit by changing service designs based on the upper level's decisions. At the lowest level, users maximise their utility while changing paths and modes of transport. Unfortunately, this model does not consider the MaaS concept or competition and cooperation between all the different MSPs in the transportation network.

More recent work by Bandiera et al. (2023) tries to include some of the aspects introduced at the end of Section 5.3 in the context of multi-modal network design problems (MNDP). In particular, they built a multi-modal network using a supernetwork approach, which can encode all possible mobility services and monthly packages. The problem is formulated as a Mathemat-

[10] https://mfc.mit.edu/simmobility

ical Program with Equilibrium Constraints (MPEC). A general profit maximisation formulation applicable to different MSPs is defined at the upper level. Users are assigned to the multi-modal supernetwork at the lower level following the traffic network equilibrium conditions. Through this approach, it is possible to study the strategies of a single MSP when competition or cooperation is present in the transportation market. However, to fully understand a MaaS multi-actor system, it is important to study how all different MSPs react when changing the system variables. On this topic, Najmi et al. (2023) developed a multi-class, multi-modal, multi-provider market equilibrium model including ride-sharing, ride-sourcing and the presence of a transport operator. For example, expanding this strategic model in the context of MaaS could help understand what happens under different scenarios.

Even though MaaS modelling has advanced in the last few years, a model that can encode all the aspects listed above generally is still missing. There are many challenges to overcome when studying the complex MaaS ecosystem. Preliminary studies on the applicability of MaaS should be done considering: (*i*) the area under examination; (*ii*) the list of the different MSPs available; (*iii*) the determination of who undertakes the role of the MaaS Broker; (*iv*) the government's involvement with the entity of subsidies and regulations.

Moreover, this model should consider that each MSP wants to maximise its profit and maintain its identity inside the market. For this reason, it is extremely important to understand the impact of different business agreements between the MaaS Broker and MSPs and how cooperation and competition between MSPs reach an equilibrium point for the entire MaaS system. These studies could be carried out through economic frameworks that try to understand different "what if" scenarios, expanding models such as the ones developed by Bandiera et al. (2023) and Najmi et al. (2023) in the context of multi-modal and multi-actor equilibrium models.

6 Discussion and Conclusion

Modelling the different interacting components of a MaaS ecosystem requires capturing the behaviour of all actors involved in offering and exploiting the services. In this light, this paper has proposed a generic framework for MaaS ecosystems (Figure 2) through a critical analysis of the existing literature to contribute to understanding and developing different building blocks of a MaaS model. Even though the number of factors influencing MaaS adoption is already high, their connections and resulting impacts on forecasting MaaS appeal remain uncertain.

While some models presented in the literature have started filling the gap in MaaS decision-making modelling, no model can fully capture users' heterogeneous travel needs and all aspects of the interaction between choices. Therefore, more sophisticated models are needed to assess potential customers' dynamic response to a change in supply characteristics. In this light, a new generation of agent-based microsimulation models may provide a promising future research direction.

Moreover, much fewer works have developed MaaS multi-actor models for the other relevant MaaS actors, i.e. the MSPs, the government, and the MaaS Broker. The intricate MaaS ecosystem presents numerous challenges that need to be addressed. It is crucial to develop an adaptable model that considers the specific area, the MaaS Broker and government roles, and the dynamics of cooperation and competition among Mobility Service Providers. Understanding the impact of business agreements is essential to achieve a balanced MaaS system.

Although the findings guide answering the study's research questions, complete models that can evaluate the entire MaaS ecosystem are still lacking. This study exclusively focuses on the first generation of MaaS, neglecting the second generation called MaaF (Hensher et al., 2023), which integrates non-transport features into the MaaS ecosystem. The study overlooks the literature review on MaaS platform implementation (Chen & Chen, 2022). As a result, the proposed framework may require future revisions. Subsequent research should aim not only to model all actors and their intricate interactions in the current framework, enabling the adaptation of traditional planning models to address MaaS-specific characteristics, but also to expand the framework to accommodate future generations of MaaS.

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Authors' contributions

The three first authors of the article contributed equally to the paper's drafting and article selection. All authors edited the paper, reviewed and analysed the results, and approved the final version of the manuscript.

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