FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Growing Artificial Societies to Support Demand Modelling in Mobility-as-a-Service Solutions

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Mestrado Integrado em Engenharia Informática e Computação

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Abstract

The increasing problems in the transportation systems, associated to a growth of the population and the continuous use of own car, have created some pressure to the governmental authorities. A possible solution for the aforementioned situation could be Mobility-as-a-Service (MaaS), a still new concept in a mobility paradigm that changes how the mobility can be delivered to the end-users. Making use the current physical infrastructures and transport means, and combining them with information and communications technologies (ICTs), MaaS has the main goal to deliver the mobility to the end-users as a service that ready to be consumed through a platform. These platforms are based on market models, where there a regulator that is responsible for the balance the balance between supply and demand.

Artificial Societies (AS) aims to be a way to simulate real societies, through an artificial model of proactive and dynamic agents, able to interact between them. These agents are able to communicate between them through a social network, where several rules are used to discipline and norm both agents and the environment where they are contained.

Demand modelling (DM) is a concept that allows accurately to forecast the demand regarding some market, depending of the balance between supply and demand. Moreover, taken into account the presence of the regulator, which is responsible for the maintenance and implementation of policies, DM facilitates the modelling of all this dynamic.

The analysis of the best service models, could prove greatly beneficial for MaaS, as modeling new and more accurate methodologies could better the decision processes present in the various market models of MaaS.

This work aims to develop a cognitive multi-agent system meta-model able to describe the dynamic of MaaS concept. The developed meta-model should be able to support different deliberative and decision making strategies in open service market environments, with mobility applications in Smart Cities. The purpose is to develop a decision support platform to support the analysis and implementation of incentive policies that promote the development of the concept of MaaS. This platform will make use of techniques of modeling and simulation of complex systems resorting to the metaphors of artificial societies and multi-agent systems.

Resumo

Os problemas crescentes nos sistemas de transporte, associados ao crescimento da população e ao uso contínuo de carros próprios, criaram certa pressão para as autoridades governamentais. Uma solução possível para a situação acima mencionada poderia ser Mobilidade como serviço (MaaS), um conceito ainda novo em um paradigma de mobilidade que muda como a mobilidade pode ser entregue aos usuários finais. Fazendo uso das atuais infraestruturas físicas e meios de transporte, e combinando-os com tecnologias de informação e comunicação (ICTs), o MaaS tem como principal objetivo entregar a mobilidade aos usuários finais como um serviço pronto para ser consumido através de uma plataforma. Essas plataformas são baseadas em modelos de mercado, onde existe um regulador responsável pelo equilíbrio entre oferta e demanda.

As Sociedades Artificiais (AS) pretendem ser uma forma de simular sociedades reais, através de um modelo artificial de agentes proativos e dinâmicos, capazes de interagir entre eles. Esses agentes são capazes de se comunicar entre eles através de uma rede social, onde várias regras são usadas para disciplinar e normalizar os agentes e o ambiente onde eles estão contidos.

A modelação da demanda (DM) é um conceito que permite prever com precisão a demanda por algum mercado, dependendo do equilíbrio entre oferta e demanda. Além disso, tendo em conta a presença do regulador, responsável pela manutenção e implementação de políticas de regulação, o DM facilita a modelação de toda essa dinâmica.

A análise dos melhores modelos de serviços, pode ser muito benéfica para o MaaS, uma vez que a modelação de metodologias novas e mais precisas poderia melhorar os processos de decisão presentes nos vários modelos de mercado do MaaS.

Este trabalho tem como objetivo desenvolver um metamodelo cognitivo de sistema multiagente capaz de descrever a dinâmica do conceito de MaaS. O metamodelo desenvolvido deve ser capaz de suportar diferentes estratégias deliberativas e de tomada de decisão em ambientes de mercado de serviços abertos, com aplicações de mobilidade em Cidades Inteligentes. O objetivo é desenvolver uma plataforma de apoio à decisão para apoiar a análise e implementação de políticas de incentivo que promovam o desenvolvimento do conceito de MaaS. Esta plataforma fará uso de técnicas de modelagem e simulação de sistemas complexos recorrendo às metáforas de sociedades artificiais e sistemas multiagentes.

Acknowledgements

I would like to acknowledge both my supervisors, Rosaldo Rossetti and Zafeiris Kokkinogenis, for all support whenever I needed any help to steer me into the right direction. Without their passionate guidance and input, this thesis would not be possible. I would also like to thank my family and girlfriend for all the patience and motivation during. Last but not the least, I would like to thank my girlfriend for being there in every moment I needed.

Manuel Gomes

"Live as if you were to die tomorrow.
Learn as if you were to live forever"

Mahatma Gandhi

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Abbreviations

AS	Artificial Society
BDM	Behavioral Differentiation Model
DARP	Dial-a-Ride Problem
DM	Demand Modelling
ICTs	Information and Communications Technologies
IOT	Internet of Things
MaaS	Mobility-as-a-Service
MAS	Multi-Agent System
MCMG	Multi-Choice Minority Game
MG	Minority Game
OD	Origin-Destination
PPP	Public-Private-Partnership
PT	Public Transport
PTA	Public Transport Authority
TM	Transport Modelling
TDM	Travel Demand Modelling
TrSP	Travelling Salesman Problem
TSP	Transport Service Provider
SP	Social Practice
SPT	Social Practice Theory

Chapter 1

Introduction

This chapter provides a presentation of the work. We start by doing a contextualization in Section 1.1, followed by a description of the the motivation and goals in Section 1.2. In Section 1.3 we present the main expected contributions of the work. Finally, we explain the organization of the document in Section 1.4.

1.1 Context

Heavy traffic congestion and longer commute times are some of the consequences of the population increase, continuation of universal car ownership and demise of fixed route public transport. While this situation has been creating some pressure on the governmental authorities to tackle the aforementioned issues, this could also prove to be an opportunity to try different approaches regarding the concept of mobility.

One particular proposed solution is *Mobility-as-a-Service* (MaaS), a relatively new concept in the mobility paradigm that suggests a big shift in terms of what is mobility and how it is delivered to the end-users. Making use of the current physical infrastructures and transport means, and combining them with information and communications technologies (ICTs), MaaS has the main goal to delivery the mobility to the end-users as a service that is consumed through a platform. These platforms are based on market models, where a regulator is responsible for the balance between supply and demand.

1.2 Motivation and Goals

MaaS is strongly proposed as a transportation system for the current and future context of mobility. Therefore, it is important to understand what components are present in MaaS and how they are structured and combined. Because MaaS offers a great variability of services, decision-makers need to understand how a population that represents a demand of travelers responds to a particular supply that is represented by the MaaS services. In this context, becomes interesting to analyze how a population adapts to the new services that can be proposed by the transport operators, as well as the new operational policies that can be applied by the authorities or managers of the mobility system. Furthermore, it is also interesting to study the emergence of new services and operational policies to respond to a behavioral change in demand. Therefore, our purpose is to study the MaaS systems in their constituent components and to propose a meta-model that captures the activities and interactions of these MaaS components.

There is complexity arising from the fact that MaaS has several decision-making actors, so they end up introducing some uncertainty into the system. On the other hand, Multi-Agent Systems (MAS) defends the appropriation of the agent metaphor to describe complex domains where the uncertainty of the human cognitive process prevails. As such, the production of a meta-model using MAS could be interesting, as it would allow to define the basic operators of MaaS and also be capable of describing the specifics of the domain in question unequivocally, evidencing the interactions between the components.

Lastly, it could be interesting to create a methodology able generate of artificial societies representing populations of travelers, in the context of MaaS, identifying the behavioral patterns defined through social practices, and then observe the evolution and adaptation of these artificial societies to the stimuli received from the system.

1.3 Expected Contributions

The main expected contribution of this work is the development of a MAS meta-model able to describe the dynamic of MaaS concept. The developed meta-model should be able to support different deliberative and decision-making strategies in open service market environments, with mobility applications in Smart Cities. Therefore, we hope to underline the grounds upon which a robust, flexible and effective decision platform can be built. The decision platform should be able to support the analysis and implementation of incentive policies that promotes the development of the concept of MaaS, making use of techniques of modeling and simulation of complex systems and resorting to the metaphors of Artificial Societies and MAS. Moreover, we expect this work to contribute for an easier implementation of incentive policies that promote MaaS, in a way that also instigate models of mobility that promote social justice between end-users.

Furthermore, we described a methodology that helps modelling the demand of a specific mobility system in the context of MaaS. This methodology proposes the generation of a demand in a form of an Artificial Society that can be instantiated at each simulation, making use of the social practices associated with each agent. Moreover, we present a technique to make this Artificial Society to grow and self-adapt at each timestep depending on the decision taken during the decision-making process and operational policies, incentives and constraints present at the mmoment of the decision.

Finally, as a proof of concept, we instantiated the proposed methodology and created a simulation model for MaaS. This model is composed by the transport modes private car, public transportation and autonomous vehicles (AV), and by an Artificial Society, where the agents of the

Artificial Society self-adapts to the supply and to the rules of the system, being also capable to guide the supply.

1.4 Structure of the Dissertation

Besides this introductory chapter, this document has the following structure. Chapter 2 presents a review of the background and state-of-the-art of the the current state of MaaS, as well as the domains of Artificial Societies and Transport Modelling, and how they could help modelling a MAS meta-model able to describe the dynamic of MaaS. Lastly there is also a brief overview of the related technologies.

In Chapter 3 the proposed solution for the aforementioned problem and its methodological approach are described. In Chapter 4 we discuss the experimental results obtained from the instantiation of the proposed methodology in the previous Chapter.

The final conclusions of this work are then presented in Chapter 5, where is emphasized the problem that is addressed and a brief overview of the next iterations.

Chapter 2

Bibliographic Review

In this chapter we make a review of the thematic concerning thus work. We start by doing a revision of MaaS and its general concepts in section 2.1. After that, in section 2.2 we describe AS and how they can be generated and in section 2.3 we analyze the problematic of TM and its important in modelling the market. Finally, in section 2.4 we make a summary of the concepts described in this chapter and also a gap analysis of the areas of study analyzed.

2.1 Mobility-as-a-Service

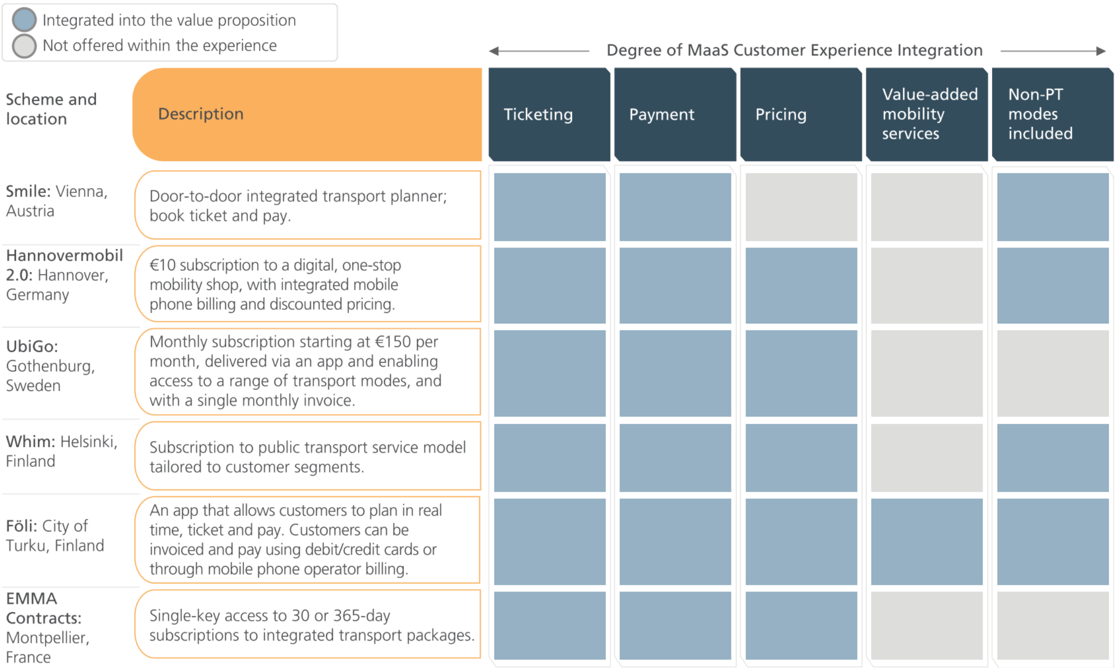
2.1.1 The concept of MaaS

MaaS is still a recent concept in the mobility field, emerging as a new transport solution for the urban areas suffering from huge traffic and congestion conditions. MaaS solutions can contribute to the goal of reducing the number of private cars, by substituting them for more sustainable ways of mobility, like PT or sharing vehicles [CC16]. Although people are tending to buy less cars, specially since the Millennial generation, the huge number of cars in the urban areas are still a problem [KS17]. Although initially thought for the urban areas, MaaS explores the concept of shared-mobility, enabling possible solutions for low in-come citizens, as well as for residents living in low-density areas [Dot16]. Hietnan et al. ([Hie15]) in a work published in 2014 describes MaaS as a mobility distribution model that is able to deliver to the customers a mobility service through a single user interface, using a service provider. This definition sees MaaS as a tailored mobility service that can be subscribed like a monthly phone or internet contract. In a different interpretation, Cox ([CC15]) emphasizes the similarity of MaaS with the communication sector.

In the work of Holmberg et al. ([HC16]), the role of subscription is seen as of great importance in the context of MaaS, as it adds the possibility to the end-users to select a route, book the service and pay it, all in just one user interface. The end goal of this approach is to build a platform that combines booking and payment, all in one single app, allowing easy use for the potential customers [Dot16]. Moreover, another work describes MaaS as a transport service combines available mobility options, facilitating the users to move from one point to another, using an integrated platform [Atk15]. The ICTs are considered as the real enabler of MaaS, allowing the transmission, collection and presentation of all the necessary information for a possible customer to identify the best transport solution that meets his/her needs [JCF+17]. Moreover, the intelligent use of ICTs enables the combination of several different transport means, some of them described below [JMM17]:

- **Public transport:** an integrated app allows the user to select and buy a ticket for a public transport trip like train or bus;
- **Car sharing:** users have the possibility to access a list of possible cars to be shared and make reservations;
- **Bicycle sharing:** users have the possibility to access a list of possible bicycles to be shared and make reservations;
- **Taxi:** users can make bookings of taxi service using the a MaaS platform.

In figure 2.1 we can see some of the current MaaS platforms already implemented.



● Integrated into the value proposition
○ Not offered within the experience

← Degree of MaaS Customer Experience Integration →

Scheme and location	Description	Ticketing	Payment	Pricing	Value-added mobility services	Non-PT modes included
Smile: Vienna, Austria	Door-to-door integrated transport planner; book ticket and pay.	●	●	○	○	●
Hannovermobil 2.0: Hannover, Germany	€10 subscription to a digital, one-stop mobility shop, with integrated mobile phone billing and discounted pricing.	●	●	●	○	●
UbiGo: Gothenburg, Sweden	Monthly subscription starting at €150 per month, delivered via an app and enabling access to a range of transport modes, and with a single monthly invoice.	●	●	●	○	○
Whim: Helsinki, Finland	Subscription to public transport service model tailored to customer segments.	●	●	●	○	●
Föli: City of Turku, Finland	An app that allows customers to plan in real time, ticket and pay. Customers can be invoiced and pay using debit/credit cards or through mobile phone operator billing.	●	●	●	●	●
EMMA Contracts: Montpellier, France	Single-key access to 30 or 365-day subscriptions to integrated transport packages.	●	●	●	○	○

Figure 2.1: MaaS progress in some cities. Adapted from [SE16]

As we can see, some applications like *Smile* in the city of Vienna and *Whim* in Helsinki already provide integration of non PT modes in their services.

The work of Kamargianni and Matyas [KM17] suggests a new player in the mobility market, referred as the MaaS provider. Moreover, Smith et al [SSK18], argues that the MaaS instead introduces two nrew roles, MaaS integrators and MaaS Operators. MaaS integrators would be responsible for integrating several TSPs which then can be operated by MaaS operators. Regarding this player, MaaS operators should deliver the integrated TSPs as a service to the end-user, though a plan or pay for use, using a single interface [SSK]. Figure 2.2 shows the suggested representation of MaaS framework.

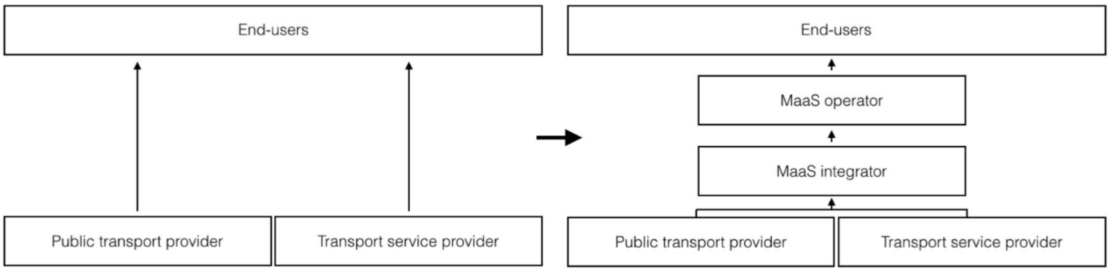


Figure 2.2: MaaS framework. Adapted from [SSK18]

Similar models to the presented in 2.2 can be found in [Lau17]. The aforementioned new roles, MaaS integrator and MaaS operator, can be either absorbed by current existing players in the mobility marker, or potentiate the emergence of new players. Furthermore, these two players working in parallel, could be a key for the development as MaaS, although is not predicted that they would replace the classic model of mobility. Intead, MaaS would be a complement in the mobility market [SSK18].

2.1.2 MaaS Development scenarios

Smith *et al.* [SSK18] in their work describe how MaaS can be implemented using 3 different scenarios, namely public-controlled development, public-private development and Market-Driven development.

In public-controlled development, the public sector is responsible not only for the planning of the PT, but also for the MaaS operator and MaaS integrator roles, as we can see in figure 2.3.

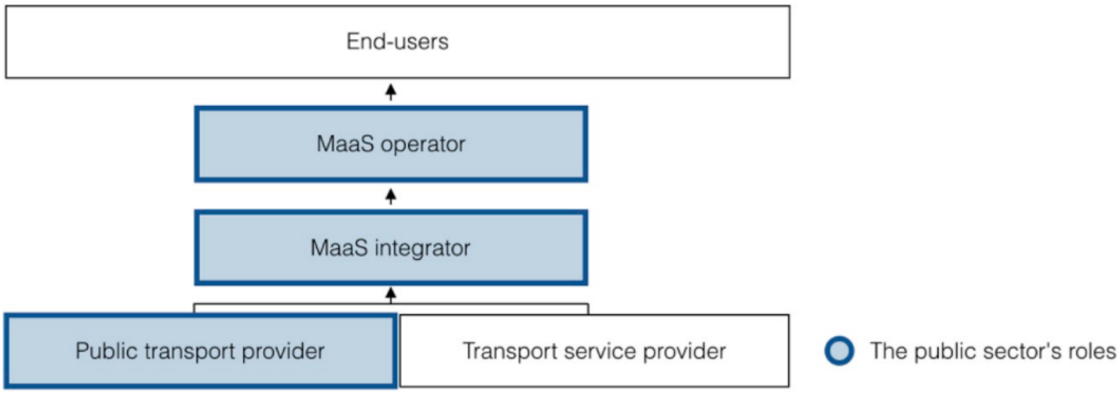


Figure 2.3: Public-controlled development scenario. Adapted from [SSK18]

Therefore, the public sector would be responsible for driving the MaaS developments, such as funding the development, implementation and operation. Public sector would also create conditions for new MaaS organizations to appear, over which they could have indirect or direct control [SSK18]. The main purpose of MaaS is facilitate a shift in transportation means, from private cars to servitized modes [T. 16]. Moreover some more reasoning for this approach is the fact that PT is considered the main backbone of MaaS and the strongest alternative to car ownership [Tra16]. Finally, some aergue that the business opportunity in MaaS ecosystem, regarding the adoption of new roles, are limited or non-existent. This is explained by the small profit margin within mobility sector and also a potential lack of customers wanting to pay for the service [SSS18].

In the second scenario, public-private development, MaaS integrator is open for the private sector, while MaaS operator remain as a responsability of the public sector, as we can see in figure 2.4.

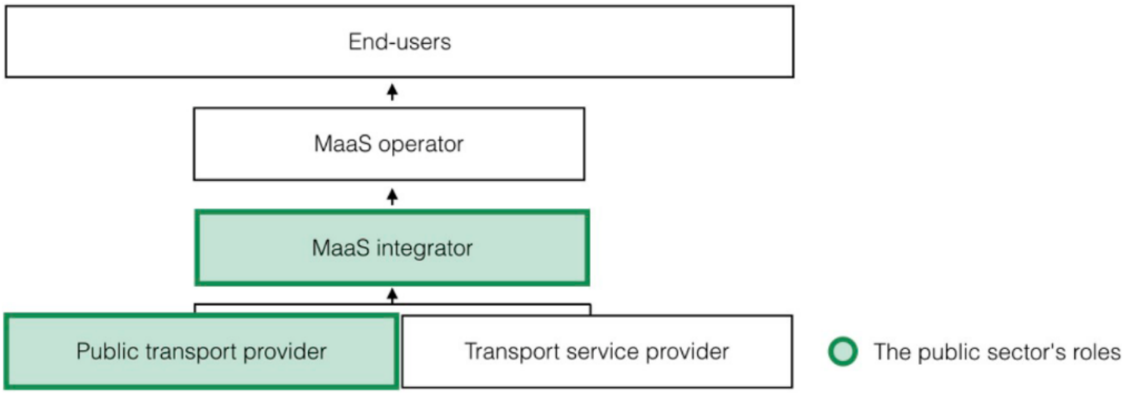


Figure 2.4: Public-private development scenario. Adapted from [SSK18]

Moreover, this scenario implies that both public and private actors keeps an active role in the concept of MaaS. This scenario holds the promise that public sector works as an enabler of the private sector, although MaaS integrator role is taken by the public sector. This can faciliatet the integration process technically and contract-wise, and as such result in a lower initial cost investment for MaaS operator. Moreover, a public controlled MaaS integrator could mitigate potential risks of MaaS operators becoming too much dominant. This could potentially avoid situations where the MaaS operators could use their role to negotiate high resale commissions, ending in unjust business deals which could potentially disrupt the service provided to the customers [SSK18].

Finally, in market-driven development, MaaS integrator and MaaS operator roles are enrolled by the private sector, such as technology or transport service providers, as we can see in figure 2.5.

In this scenario, the mission of the PTAs are more or less the same as the current same, where they are responsible for planning traditional PT. Nevertheless, they have some added responsibilities such as offer viable deals for third-party platform resellers, through MaaS operators, as make possible for third-party actors to deliver the PT tickets through a digital platform to the end-users [LV17], and facilitate the bundling with other transport modes as an integrated service [HC16]. Therefore, in market-driven scenario, the public sector would have as a main role work as PT providers, assuring and facilitating the integration of the PT service as a bundle to be delivered

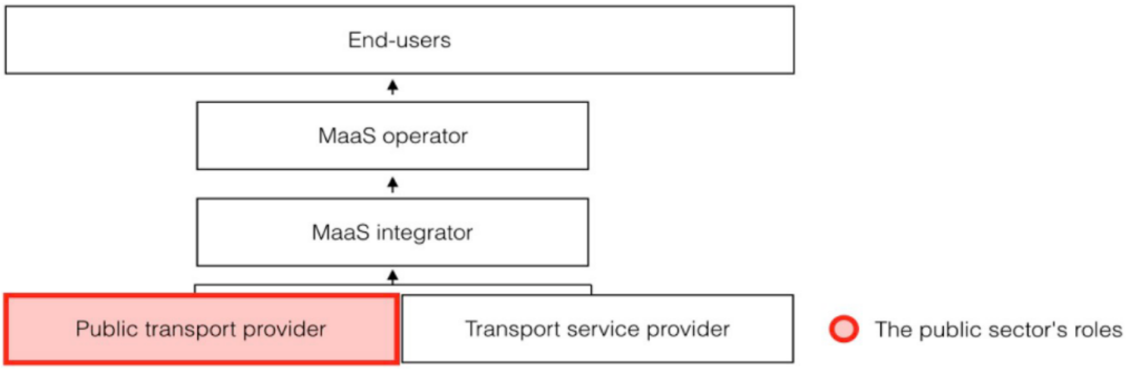


Figure 2.5: Market-driven development scenario. Adapted from [SSK18]

and consumed by the end-user, using some digital platform. Moreover, public sector in this scenario works more as an enabler, rather than the major force, as private sector is expected to take this role and push the development. The reasoning for this development scenario is in the fact that private actors have better capabilities and higher incentives to develop innovative services that meet the end-users needs, compared to the public sector [SSK18]. Neverthless, public authorities would still need to invest in digital technology and business develop, in a way that enables to make PT tickets possible to be reselled. Therefore, an high-capacity and innovative PT is still a prerequisite for the development of a viable MaaS [LV17].

2.1.3 Ecosystem of MaaS

In the context of MaaS, a major integration of several different transport services which are then provided to the traveler through a single interface allows for minimization of the boundaries between the different transport modes. As such, the MaaS ecosystem includes transport services and infrastructure, modes, ticketing and payment services. Ultimately, the main purpose of MaaS is not build more capacity in the transport system, but rather increase the capabilities and capacity in a smarter way.

In this section we will present the main stakeholders of MaaS ecosystem, as well as the emerging service combinations and business and operators models.

2.1.3.1 Stakeholders

The MaaS stakeholders have distinct roles to play in maximizing the chances of success for themselves and seamless mobility services. Therefore, the expectations and ambitions of stakeholders will determine the possible adoption and usage of MaaS by the travelers.

Table 2.1: Stakeholders present in MaaS ecosystem. Adapted from [KEA$^+$16]

Sub-organization	Description
Traveler	All services to be included are designed to benefit the traveler. The traveler is the end-user. The level of automation in every single interaction should determine the level of MaaS.
MaaS Operator	The subgoal to achieve achieve is "Generate Mobility Packages". It will loosely interact with other portions of the system because of the dependencies "Provide Mobility Package" and "Subscribe or pay Mobility Package" with User, "Provide Accessibility contracts" with Authority, and also "Provide Mobility Packages" and "Provide timetables and capacity" with Transport Operator.
Technology Providers	Provide technological mobility solutions for the roadside, smart phone apps, wearables, onboard and central systems. These must comply with the legislation and policies established by government and be acceptable to the traveler and mobility providers of the jurisdiction. In addition, contribute to define open standards (data and architecture) for IoT generalized presence and work as differentiation enablers for travelers, operators and meta-operators.
Transport Operator	The subgoal to achieve is "Transport User to destination". Interaction depends on the dependencies "Provide Mobility Packages" and "Provide timetables and capacity" with MaaS Operator Operator, and "Update stops and stations" with Authority.
Authority	Coordinate, administer, legislate, and moderate mobility services in the jurisdictional entity. The goal is a benefit, overall range of mobility services for citizens in their jurisdiction. Central Government creates the legal and administrative framework that allows MaaS to happen, acting as the catalyst by promoting mobility policies and supporting legislation for open standards, as well as privacy and economic protection for its citizens.

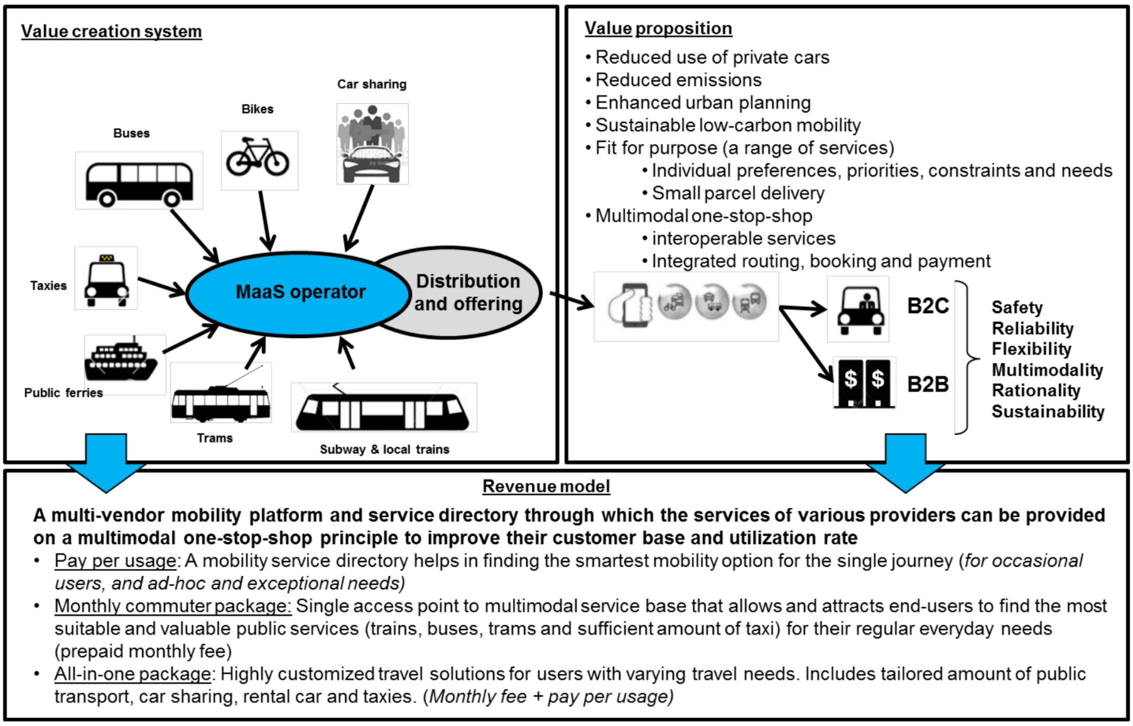
As we can see in Table 2.1, the only new stakeholder in the context of the transport systems is the MaaS Operator, as the others are already present.

2.1.3.2 Service Combinations

In MaaS ecosystem seems to be emerging several different services combinations. They can be classified as urbna, suburban and rural, but also, with a bigger demand for single market transport systems in areas regions like Europe, national and international levels of service are also appearing.

Each of the combinations is analyzed considering value creation system, value proposition and revenue model.

In urban areas, the main objective of MaaS is to reduce the traffic, parking problems and emissions, through the reduce of the use of private cars, allowing to a better planning of the transport system [KEA+16]. One advantage of the urban areas is the quantity of different transport modes and, as such, different services combinations becomes easier to create. Therefore, there are higher possibilities to provide services to the travelers that allow them to become less dependent of the use of private car. Urban areas also allow different revenue models for the MaaS operators, because of the higher amount of possible customers. Figure 2.6 shows in more detail the MaaS in urban areas.

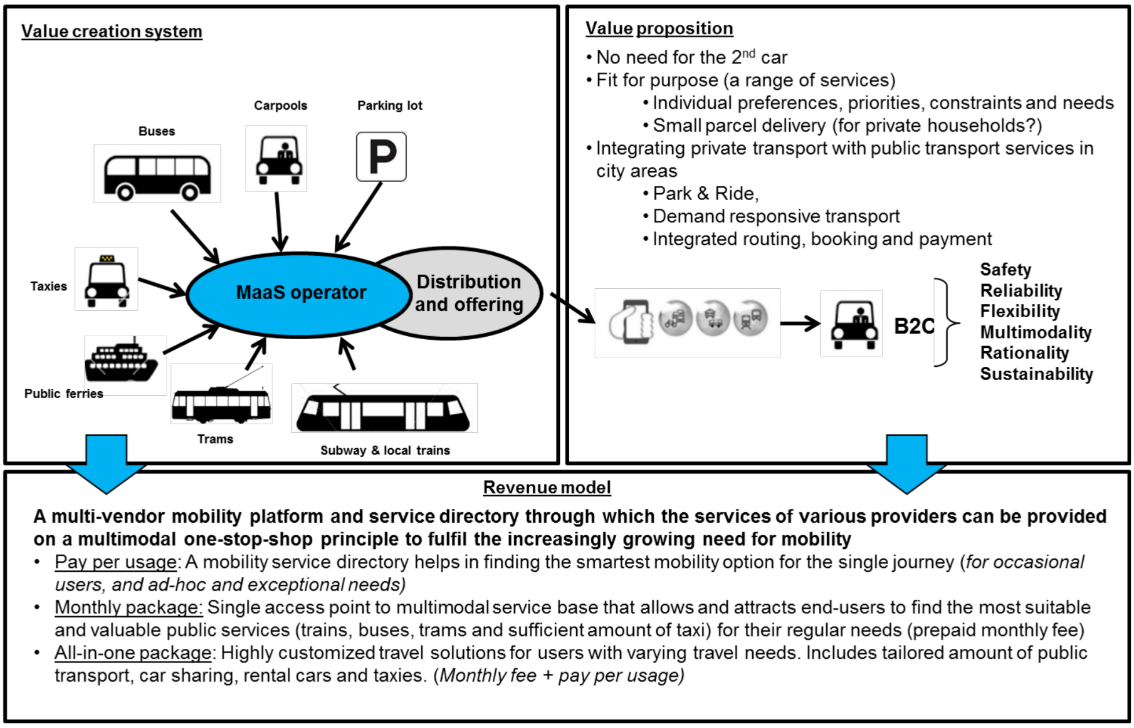


A multi-vendor mobility platform and service directory through which the services of various providers can be provided on a multimodal one-stop-shop principle to improve their customer base and utilization rate

- Pay per usage: A mobility service directory helps in finding the smartest mobility option for the single journey (*for occasional users, and ad-hoc and exceptional needs*)
- Monthly commuter package: Single access point to multimodal service base that allows and attracts end-users to find the most suitable and valuable public services (trains, buses, trams and sufficient amount of taxi) for their regular everyday needs (prepaid monthly fee)
- All-in-one package: Highly customized travel solutions for users with varying travel needs. Includes tailored amount of public transport, car sharing, rental car and taxies. (*Monthly fee + pay per usage)*

Figure 2.6: MaaS services in urban areas. Adapted from [Eck16]

In suburban areas, the availability of public transportation is more limited compared to urban areas. Therefore, the populations becomes more dependent in car ownership. Figure 2.7 describes the MaaS in suburban areas. One way that MaaS can improve the transport services in these areas is through the integration of taxis and other modes of demand-responsive transport with the public transport [KEA+16]. On the other areas, suburban areas are also potential locations to explore the concept of ride-sharing and carpooling, by proving extensive park and ride facilities. Therefore, the elimination of private cars in these areas is not a good option, but the need of a second car in a family may be reduce through good alternatives of transportation. Regarding the payment method, pay-per-use seem to be the most adequate, as the different needs of the travelers can be better attended.



Value proposition

- No need for the 2nd car
- Fit for purpose (a range of services)
  - Individual preferences, priorities, constraints and needs
  - Small parcel delivery (for private households?)
- Integrating private transport with public transport services in city areas
  - Park & Ride,
  - Demand responsive transport
  - Integrated routing, booking and payment

Revenue model

A multi-vendor mobility platform and service directory through which the services of various providers can be provided on a multimodal one-stop-shop principle to fulfil the increasingly growing need for mobility

- Pay per usage: A mobility service directory helps in finding the smartest mobility option for the single journey (*for occasional users, and ad-hoc and exceptional needs)*
- Monthly package: Single access point to multimodal service base that allows and attracts end-users to find the most suitable and valuable public services (trains, buses, trams and sufficient amount of taxi) for their regular needs (prepaid monthly fee)
- All-in-one package: Highly customized travel solutions for users with varying travel needs. Includes tailored amount of public transport, car sharing, rental cars and taxies. (*Monthly fee + pay per usage)*

Figure 2.7: MaaS services in suburban areas. Adapted from [Eck16]

Next, regarding MaaS in rural areas we can see a complete description in Figure 2.8. Although a majority of the population currently lives in urban and suburban areas, there are still a significant amount of population living in rural areas. Therefore, building services through MaaS concept that address this specific situations are of relevant importance, specifically when considering the social justice among all the population independently of where a person lives. One issue with the rural areas is the lack of connections to long-haul and scheduled services, which can be an opportunity to increase the number of transport services in this specific usage [KEA+16]. Pay-per-usage seems to be the most plausible revenue model because the demand is hard to predict in this areas.

MaaS on national and international levels is a new concept even among the other combinations of service. This new kind of service is emerging in regions where different countries aim for the concept of single market in transportation, such as Europe [KEA+16]. Therefore, this service aims specially for long-haul travel, and, as such, air traffic becomes an essential component of the MaaS service [KEA+16]. Figure 2.9 presents in more detail the concept of MaaS on national and international levels.

2.1.3.3 Business and Operator Models

There are for main MaaS operator model categories: public, commercial, Public-Private-Partnership (PPP) and PPPP. This last category means public transport covering also shared resources.

The public category integrates other transport services like carpooling, taxis or city bikes with the services provided bu the public transportation. The main purpose of this model is to

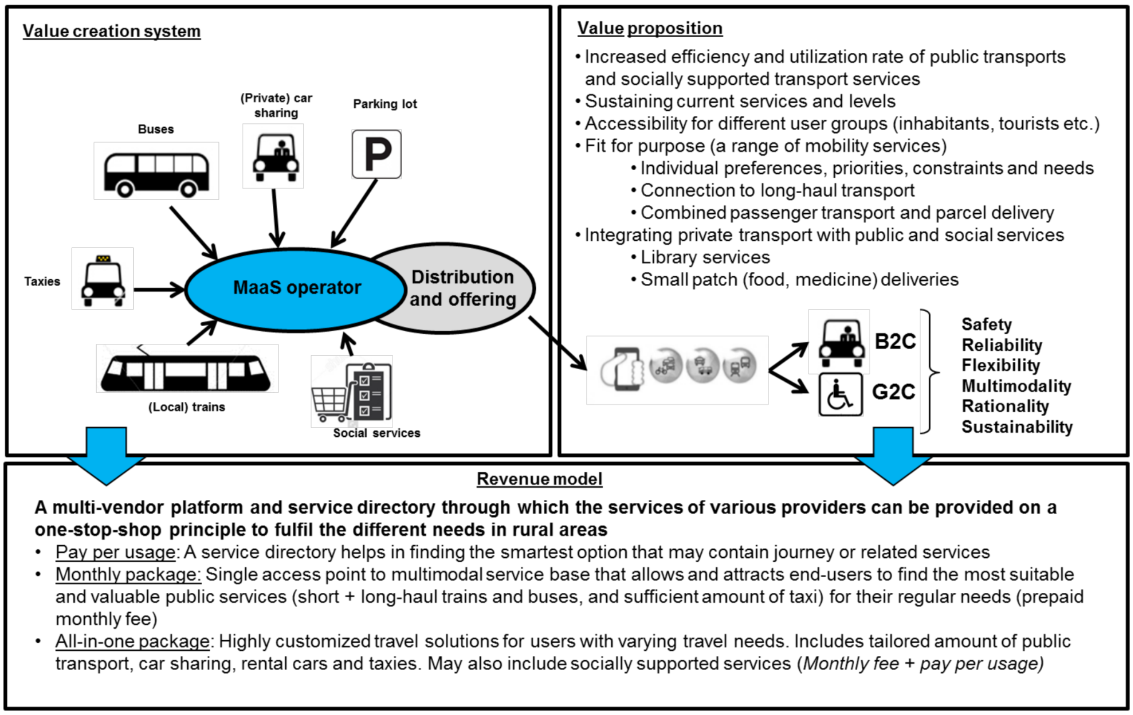


Figure 2.8: MaaS services in rural areas. Adapted from [Eck16]

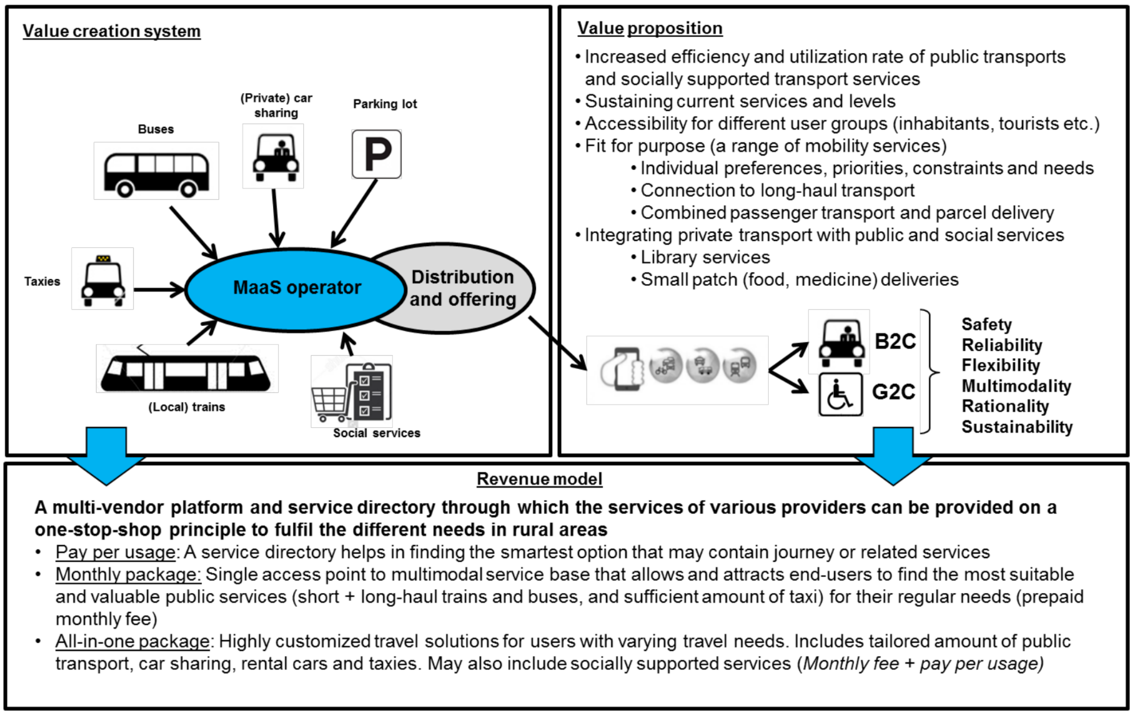


Figure 2.9: MaaS on national and international levels. Adapted from [Eck16]

increase sales and the occupancy of the transports, while also pursuing for the reduction of emissions [Eck16]. Regarding the commercial category, it may be splited in integrator and reseller

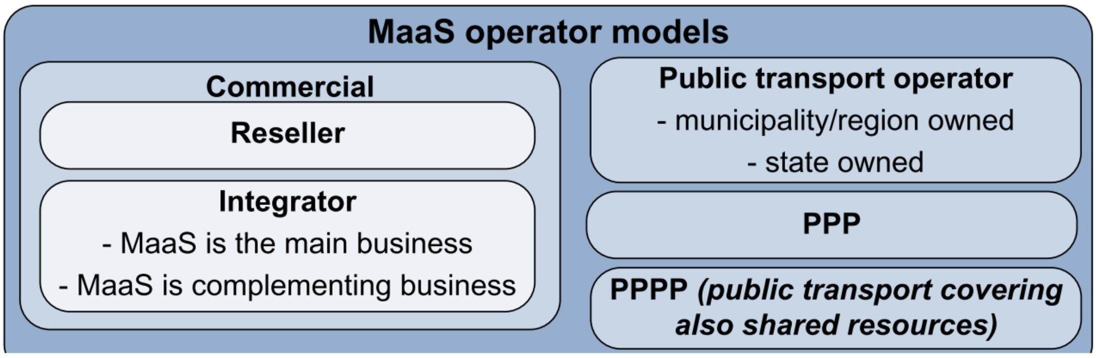


Figure 2.10: Business Models of MaaS. Adapted from [Eck16]

types. The commercial integrator category combines several modes of transportation with the ICTs, allowing for the trip planning, ticketing and even payment. On the other hand, the reseller category simply resupplies the transport services from different transport operators. As such, this category allows the transport operators to either focus their business entirely in MaaS or just use it as a complement. The reseller model is based mostly in commission and as such is highly dependent on high volumes since the margins are minimal [Eck16].

In PPP the public actor combines several types of services in order to enhance the services that are being provided to the travelers. This model does not necessarily aims for profits, but instead for the increase of occupancy and social inclusion. The PPPP is an extended version of the PPP category that targets the rural areas, where the share or resources is important to improve the quality of the transport system [Eck16].

2.2 Artificial Societies

Artificial Societies can be described as a computerized model, consisting of independent agents, able to describe simulated real societies. In the specific application domain of this dissertation, artificial societies underlie the grounds upon which the concept of Artificial Transportation Systems can be effectively implemented [RLT11, RL15].

Therefore, this concept is of great usefulness when we need to verify the effect of change of some parameter that alters the balance in the agent ecosystem, in order to test this change before implementing them in a real society. Moreover, synthetic populations may play a paramount role in testing crowd management strategies, especially in situations of crises and risk [ARC11, AKR12].

Epstein and Axtell describe a method able to generate an AS based on three parts: an environment, a population and a set of rules [EA96]. In their definition, they approach AS as agent-based, but where the agents only have a small number of attributes. Therefore, they lack personality and other believable characteristics. While they are not networked together since generation phase, they form, however, bonds and relationships at runtime, as the set of rules of the environment promote this behavior [EA96].

In a work, an algorithm is proposed, that is able to examine large networked populations in order to find densely connected sub-networks or communities, was proposed [BGLL08]. This algorithm has been used in AS generation method, also known as friend attachment model. In this model, the social network grows at each timestep, at which, all the network is divided in different communities using this algorithm. After that, each new agent created is associated with a random community, or linked with some random agents over the population [BGLL08]. As time progresses, the networks are reevaluated and becomes clearer which communities of agents are interconnected.

2.2.1 Population Generation

Lacroix and Mathiew proposed in their work a model for generating an artificial society, based in determined demographics of a population. This model, used for vehicular drivers, uses unsupervised learning from a sample of data, which then is used to determine the agent classifications and parameters [LM12]. This generation model is named Behavioral Differentiation Model (BDM) and the behaviors of the agents during simulation are described using a *social norm* metaphor.This model can be see in figure 2.11:

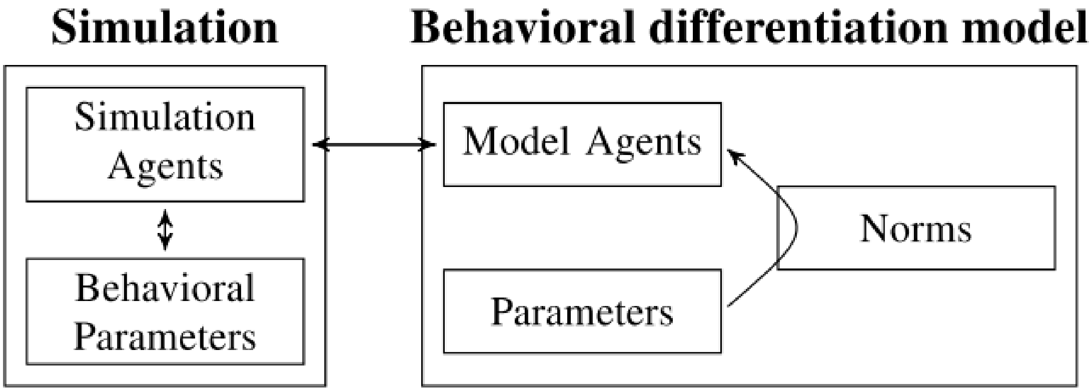


Figure 2.11: Behavioral Differentiation Model. Adapted from [LM12]

In this model, the norms describe the behavioral patterns, that are used to specify the behaviors of the agents. Moreover, the norms also allow the generation of parameters of the agents in the creation phase, enabling to control them at run time. Furthermore, model agents work as middleman between the simulation and the model. A norm is instantiated in a model agent during the creation of the simulation agents. After that, the simulation agent models receive the values of the corresponding model agents. Finally, the conformity of the simulation is controlled through the model agents during runtime 2.11.

In another work, a simulation is done to estimate the evolution of Britain using historical census data in order to calculate the demographics for the following decade [BCD+05].

In another simulation, an agent-based population was developed to help track the spread of H1N1 influenza. At each agent was assigned demographic attributes, being then connected using a social network. The agents had a health status used to track they state regarding the infection of H1N1 influenza. During the simulation, the infected agents could spread the disease to those who were near them [GLQ+13].

2.2.2 Believable Agents

An agent is considered believable when is considered autonomous and therefore able to make rational decisions. A generalization based on the Turing test suggests that agents can be labeled as believable when their behaviour causes the audience to "suspend their disbelief" that they are actually virtual [Loy97]. Therefore, agents are believable if they have individual traits, describing their personality, that have an effect on they decisions that they are able to make. In a work are described the seven requirements for and agent to be believable: Emotion, Personality, Illusion of Life, Self-Motivation, Consistency of Expression, Social Relationships and Change [Loy97].

Personality and emotions have been the foundation for an agent in AS [Hin12, BS13]. Therefore, agents have been described using human behaviors as models to follow, as these psychosocial elements are important for creating believable agents [Hin12, RDB03]. In a work about Psychosocial Behavior, models of emotions and personality traits are described as hierarchical among them. As such, each behavior has a specific weight which makes them more or less important to the modelling of an agent, depending how it stands compared to others behaviors.

2.3 Transport Modelling

2.3.1 Demand-Side Modelling

TM allows the estimation of travel demand using current travel behavior to predict future travel patterns, using a sample of travel behavior data [BAR15, AAA+17, AFR19]. This analysis offers the advantage of helping to answer questions like "what if" about proposed policies and plans. Figure 2.12 shows a proposed framework approach for travel forecasting:

Therefore, transport demand modelling can be described as a computer model able to forecast travel behavior and demand, based on a number of assumption [JCF+17]. Demand models have evolved from static to dynamic forecasting models, getting the main focus on the heterogeneity of individual traveling, meaning that a evolution was aggregate to a disaggregate representation of travel was performed [BABG+07]. In this direction, initial efforts have suggested the appropriateness of multi-agent systems to model various aspects of traffic demand [RLCB02, RBB+02, RL05b, RL05c].

Several approaches for travel demand modelling, categorized by their nature, were proposed. The current dominant aggregate modelling approach is the four-step modelling process. In figure 2.13 we can see the main steps of this process.

In trip generation, the starting and ending points of the trips are generated, width each trip being associated one or more users. In trip distribution, the generated trips in the previous step are

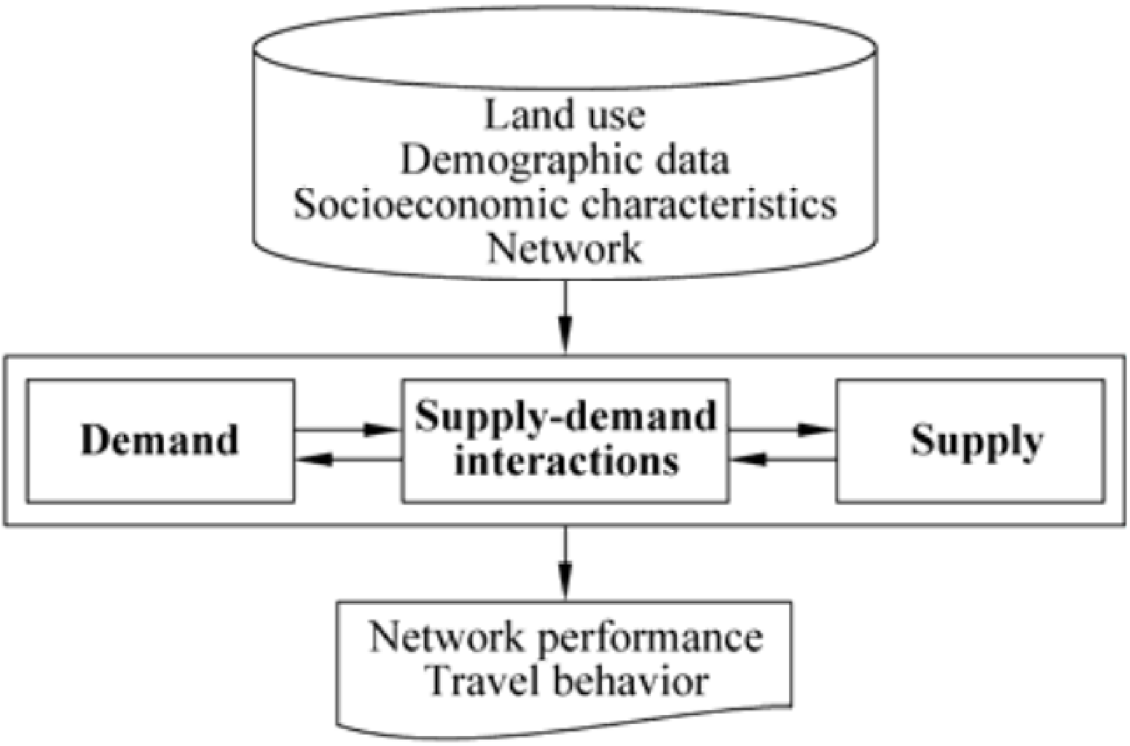


Figure 2.12: Travel forecasting framework. Adapted from [BABG+07]

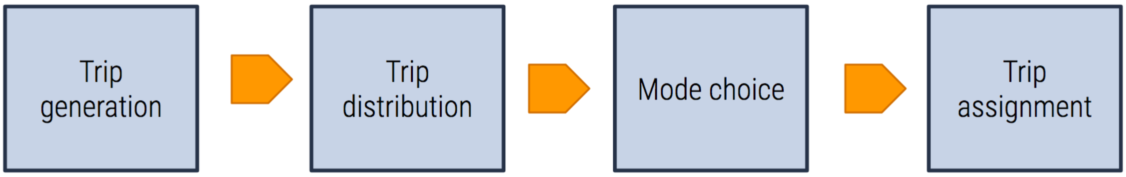


Figure 2.13: Four-step modelling

distributed in time and space. In the next step, mode choice, a transport mode is selected. Finally, in the last step, the route of each trip is defined.

Furthermore, in the activity-based approaches, interdependencies and integrity of trips from the same trip chain are of crucial importance, as these represents a dynamic interaction of tasks, needs and constraints of the demand model [RT14]. Moreover, rule-based models allowed the creation of transportation activity schedules based on decision rules and heuristics. Some new approaches have emerged including agent-based modelling and time-space prisms and constraints [BK99, TAJ02, RL05a]. These activity-bases models assume that travel decisions are made in conditions of certainty. However, this may not prove realistic, as there are several factors adding uncertainty to the state of transportation systems. Moreover, introducing uncertainty in the decision-making process makes important the identification and consequent exploration of other drivers of travellers' choice behaviours. These should be considered when modelling travel demand, as MaaS is described as a complex and dynamic mobility system [JMM17]. ICTs and smartphone have a great contribute to activity-based modelling techniques, as they help users to better organize their daily activities. Therefore, understanding how to expand activity-based models and their choice models is of crucial importance to understand the travel behaviour and decision-making process in MaaS context. In another work, a new activity-generation module was developed using microscopic travel demand model. This new approach could allow for a better understanding about how changes in travel behavior can be reflected in the transport demand model [HKSB16].

Currently there are not many studies underlining the impact of MaaS on end-users travel behavior. Therefore studying this thematic can greatly contribute for the improvement of policies related to MaaS.

2.3.2 Supply-Side Modelling

The supply-side modelling is focused in the transport means offered by the transport services [SKK14]. In this context, MaaS represents a big disruptive concept as a consequence of a integration of several transport means such as PT and share services, like car-sharing or bicycle-sharing. Therefore, the flexibility and the one-way configuration that MaaS brings to the end-users, represents some major challenges, specially concerning the relocation strategies and vehicle fleet optimization [CFP14]. A possible solution for the car-sharing relocation problem, may pass by the autonomous vehicles, as they could balance themselves in an automatic way [ZSFP11].

Another problematic regarding on-demand transportation service are the individual services, like Uber-like services or regular taxis. The main problem with this kind of services is in the design of the routing strategy of the vehicles. While a widely used algorithm to deal with this problem is DARP, which is based on the TSP, some heuristic search algorithms have proven to calculate optimal solution for these routing problems [JCF+17]. Furthermore, intermodal mobility planning also needs some research, as its still limited. Currently the main approach is applying concepts of constraint-satisfaction-problems and graph theory [MLK13].

The MaaS integrated platforms can be used to better understand travel patterns. Moreover, these platforms can also be used to improve the location of critical points for the supply-demand optimization [JCF+17]. The real-time information that the MaaS platforms can provide to the users may prove important regarding the ability to update the dynamically the user's perception of the travel alternatives [CMV06].

2.4 Chapter Summary

In this chapter we reviewed several concepts and how they address some of the subjects of the work theme. Regarding that, we summarize some of the main works in the table 2.2, where we make a gap analysis.

As we can see, we couldn't find a document embracing all the referred topics in a single work, while giving some more insights about how to promote and implement MaaS in workable ans sustainable way . As such, revisiting all these study areas, we propose a methodology that uses

Table 2.2: Gap Analysis

Author(s)	**Transports**	**SE**	**MaaS**	**AS**	**MAS**	**DM**
Smith et al., Kamargianni et al.	x		x			
Lacroix and Mathieu	x			x	x	
Epstein and Axtell				x		
Kamau et al.	x		x			x
Shaheen et al., Standing et al.	x	x				

the metaphor of MAS to analyse the MaaS and to create an Artificial Society that represents the demand and is able to evolute and self-adapt.

Chapter 3

Methodological Approach

In this chapter we discuss the methodological approach adopted to solve the defined problem in section 1.2. In chapter 2 we reviewed the main concepts regarding MaaS, artificial societies, and demand modeling. After that, we've made a gap analysis where we identified an opportunity to develop a meta-model based on the MAS metaphor able to describe the demand modeling in MaaS, using artificial societies.

Therefore, we propose a meta-model able to describe the structure and dynamics of the MaaS concept. In section 3.1 we describe the Analysis and Design of the MAS model. In order to do that, we follow the work of Castro and Oliveira [CO06] that proposes some complements to the Gaia [ZJW03] methodology. The main contribution of their approach in the analysis and design of MAS is the combination of different methodologies, such as Tropos [GMA02] for the requirements elicitation and Gaia for the analysis and design of the system. We enhanced their proposal by including interaction-oriented elements and behavioural patterns that agents use to evolve within a society. Therefore, we use Interaction-Oriented Design of Agent simulations (IODA) for the modelling of the interactions between the agents, which allows to define in a more microscopic way each interaction, easing the instantiation of the meta-model in a simulation platform.

Our approach to the problem was conceived considering artificial societies as the demand part of a MaaS ecosystem. Thus, in section 3.2 the approach to demand modelling is presented and is divided between: a) the automated generation of social practices (SP) from a sample of data to model an artificial society of *travelers* representing the demand, and b) the growth and evolution of such a society through *self-adaptation*, using Clonal Plasticity [NC18] and Reinforcement Learning relying on Roth's and Erev's algorithm [RE95]. Here, social practices are meant to be a set of actions or activities within a context having a meaning and physical elements [MDJ18]. Figure 3.1 presents the proposed methodological approach and how we intend to iterate through it.

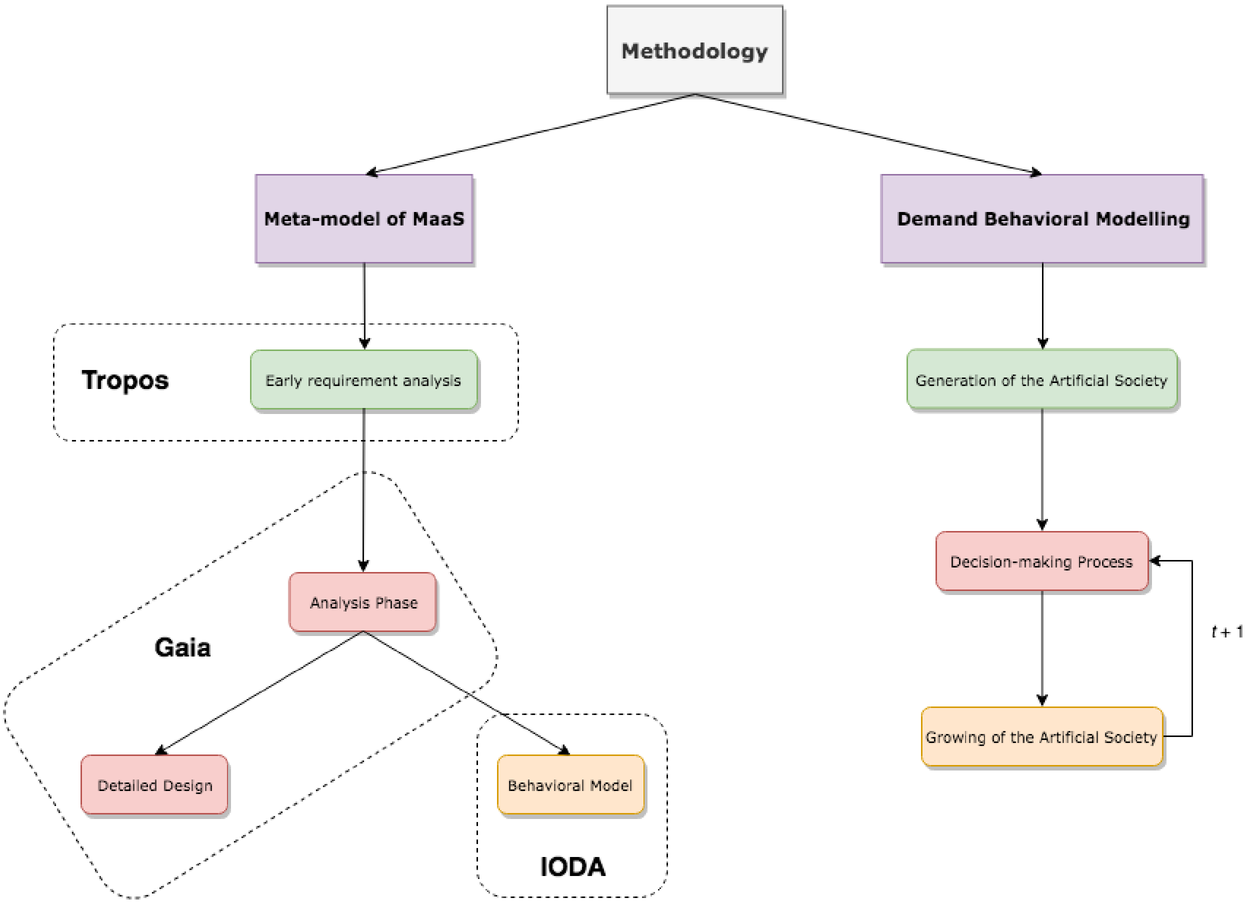


Figure 3.1: Decision-making process in MaaS.

3.1 Analysis and Design

3.1.1 Early requirements analysis

In early requirements analysis we define a goal-oriented perspective for MaaS using Tropos [GMA02]. This analysis provides a more natural view of what is observed in reality [Lub07], helping in the identification of role basic functionalities, specific organizations, and so forth [PRG11, PRG14]. We rely on the Taxonomy of MaaS described in section 2.1.3 to accomplish the analysis. The resulting actors and goals can be seen in the main diagram depicted in Fig. 3.2.

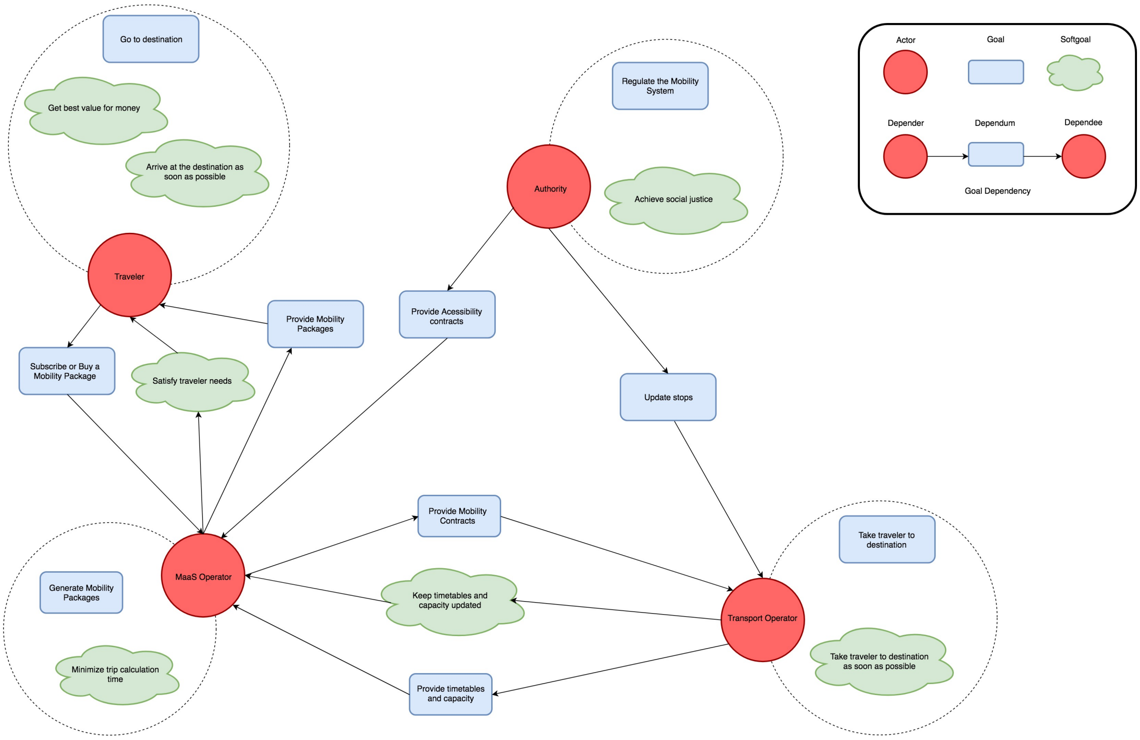


Figure 3.2: Actors and goals main diagram (partial).

In the actors and goals main diagram we can identify several different concepts, namely *actor* representing an agent or role, *goal* which is what an agent or group of agents are aiming to accomplish, and finally *soft-goal* that are secondary desires agents want to achieve and are associated with quality of service, security, and so forth [vL01].

The *Traveler* actor has the goal to reach a destination, but aims to do it for the best monetary value, while also arriving to the destination in the minimum amount of time. In order to accomplish the goal, the *Traveler* may either subscribe or buy a mobility package generated and provided by the *MaaS Operator*. Therefore, the main goal of the *MaaS Operator* is to generate mobility packages that integrates a range of transport services into bundles, while trying to minimize the calculation time and satisfying the *Traveler* actor needs. In order to accomplish the goal, the *MaaS Operator* uses the information of the timetables and capacity of the *Transport Operator* actors with whom it has a mobility contract. The main goal of the *Transport Operator* actor is to transport a *Traveler* to his/her destination in the minimum amount of time possible.

The *Authority* actor has as main goal to regulate the mobility system, while aiming as soft goal to achieve social justice among all the *Traveler* actors of the system. Moreover, *Authority* is also responsible for providing accessibility contracts in order to a *MaaS Operator* to have permission to operate in the mobility system, as well as updating the stops and stations of the transport network.

3.1.2 Analysis Phase

The main goal of the analysis phase is to organize the early requirements and specifications of the previous phase into a more technical level. The result of this analysis is the generation of a) a set of sub-models consisting of a division of the system into sub-organizations, b) an environmental model, and c) a role model. Regarding the interaction model, we will further discuss it in section 3.2.

3.1.2.1 Sub-organizations

The identification of sub-organizations within a particular system allows the modelling of a real world scenario into a more modular way. As such, each sub-organization must have a specific behaviour towards a common sub-goal of the system, while interacting loosely with other portions of the system. Furthermore, any required competences should not be needed by other entities of the system. The identified sub-organizations of MaaS ecosystem are described in Table 3.1.

Table 3.1: Identified sub-organizations

Sub-organization	Description
Travelers	The sub-goal to achieve is "Go to destination". It will loosely interact with actor *MaaS operator* because of the dependencies "Provide Mobility Package" and "Subscribe or pay Mobility Package".
MaaS Operators	The sub-goal to achieve is "Generate Mobility Packages". It will loosely interact with other portions of the system because of the dependencies "Provide Mobility Package" and "Subscribe or pay Mobility Package" with *Traveler*, "Provide Accessibility contracts" with Authority, and also "Provide Mobility Packages" and "Provide timetables and capacity" with *Transport Operator*.
Transport Operators	The sub-goal to achieve is "Transport *Traveler* to destination". Interaction depends on the dependencies "Provide Mobility Packages" and "Provide timetables and capacity" with MaaS Operator Operator, and "Update stops and stations" with Authority.
Authorities	The sub-goal to achieve is "Regulate the Mobility System". It will loosely interact with other portions of the system because of dependency "Provide Accessibility contracts" with MaaS Operator and "Update stops and stations" with *Transport Operator*.

3.1.2.2 Environment model

In the environment model we identify and describe the resources available to the agents in the system. These resources are described by Gaia as variables or tuples that can be consumed or extracted by the environment. The identified resources of MaaS ecosystem are described in Table 3.2.

Table 3.2: Resources

Name	Description
travelerProfile	Contains information about the *Traveler*, including their frequent destinations and credit information as well. It will allow the implementation of "Subscribe or Buy a Mobility Package" and "Transport Traveler to destination".
tripRequirements	Requirements of origin/destination of a *Traveler*. It will allow the implementation of "Generate Trip" and "Transport Traveler to destination".
trips	Trips generated according to the requirements specified in *tripRequirements* by a *Traveler*. It will allow the implementation of "Generate Mobility Packages" and "Transport Traveler to destination".
transportOperatorProfile	Contains information about the *Transport Operator*, including their current fleet and legality to operate. It will allow the implementation of "Subscribe or Buy a Mobility Package" and "Transport Traveler to destination".
mobilityPackage	Contain information about the mobility packages created according to the transport operators integrated in *MaaS Operator*. It will allow the implementation of "Generate Mobility Packages".
vehicle	Contains information about a vehicle used by the *Transport Operators* to transport the *Travelers*. It will allow the implementation of "Transport Traveler to destination" and "Provide timetables and capacity".
transportTimetable	Contains information about the timetables of all *Transport Operators* with Mobility Contract with the *MaaS Operator*. It will allow the implementation of "Generate Mobility Packages".
mobilityContract	Contains information a mobility contract made between a *MaaS operator* and a *Transport Operator*. It will allow the implementation of "Integrate Transport Operator".
policy	Contains information about the policies and the regulation of the MaaS ecosystem. It will allow the implementation of "Provide Accessibility contracts" and "Update stops and stations".
transportNetwotk	Contains information about the transport network, including all the links of the system, used by the *Transport Operators* and *Travelers* in the system. It will allow the implementation of "Transport Traveler to destination" and "Provide timetables and capacity".
stopsAndStations	Contains information about the stops and stations used by the *Transport Operators* and *Travelers* in the system. It will allow the implementation of "Transport Traveler to destination".

3.1.2.3 Role model

In Role Model we identify some characteristics of the system that will remain independent whatever the organizational structure is taken. These characteristics are basic skills required by the organization to fulfill its goals and their identification is facilitated by the goal-oriented approach adopted in the early requirement analysis. For each role, *activities*, *protocols*, *permissions*, and responsibilities are defined. *Activities* are actions performed by the agent without interact with any other role, while *protocols* are actions that may involve other roles. Moreover, *permissions* describe the available resources to the agents, that can be write, read or changed. Lastly, the *responsabilities* define the functionality of the role, being able to be of one of two types. The *responsabilities* of type *safety* are properties that must be always preserved regardless of the scenario of the action to be performed, whereas the *liveness* properties describe a generalized lifecycle pattern of the role [CJSZ04]. In order to better express the *liveness* properties, several operators are used to describe this type of properties, as we can see in Table 3.3.

In the context of MaaS we can identify several roles that represent the basic skills of the system: TRAVELER, TRANSPORTSERVICEPROVIDER, TRANSPORTTIMETABLEGENERATOR, INTEGRATOR, TRIPPLANNER, PAYMENTOPERATOR, MAASMANAGER, POLICYMAKER and STOPANDSTATIONPLANNER. In the following tables we present the identified roles.

Table 3.3: Operators for *liveness* expressions

Operator	*Interpretation*
$x.y$	x followed by y
$x \mid y$	x or y occurs
x^*	x occurs 0 or more times
$x+$	x occurs 1 or more times
x^ω	x occurs infinitely often
$[x]$	x is optional
$x \mid\mid y$	x and y interleaved

The purpose of the role TRAVELER is to ensure that a TRAVELER makes a request for transportation whenever needing to move from one point to another. In order to travel using MaaS, the TRAVELER must create a *travelerProfile* with his/her personal information, frequent destinations and credit information. With a *travelerProfile* created, the TRAVELER can generate the *tripRequirements* and then either pay as go or subscribe a *mobilityPackage* if she/he has the purpose to travel with MaaS more frequently. The schema for the TRAVELER role is specified in Table 3.4.

Table 3.4: Schema for TRAVELER

Role Schema: TRAVELER

Description:

Makes requests for transportation. TRAVELER can pay as go or subscribe a mobility package.

Protocols and Activities:

GenerateTravelerProfile, InformMaaSOperator, GenerateTravelRequirements, MakeRequestForTravel, SelectGeneratedTrip, SelectMobilityPackage, PayBill, PaySubscription

Permissions:

generates: *travelerProfile*, *tripRequirements*
reads: *travelerProfile*, *mobilityPackage*, *trips*
changes: *travelerProfile*, *tripRequirements*

Responsibilities:

Liveness:

TRAVELERPROFILE = (GenerateTravelerProfile . InformMaaSOperator) || (UpdateTravelerProfile . InformMaaSOperator)

Safety:

true

The TRANSPORTSERVICEPROVIDER role specifies the responsibilities related to the transportation of a *Traveler* between an origin and destination points. During the *liveness* of the role, the TRANSPORTSERVICEPROVIDER can either have fixed transport routes, with fixed stops and itineraries or work as on-demand and reroute dynamically to accommodate the requests received by a TRAVELER. Therefore, the TRANSPORTSERVICEPROVIDER must have access to the *tripDetails* and have as *safeness* a non-negative *currentCapacity* and a positive *currentCapacity* as a condition to accept transport requests. In Table 3.5 the TRANSPORTSERVICEPROVIDER role is described in mode detail.

The TRANSPORTTIMETABLEGENERATOR role is responsible for generating the *transportTimetable* of a particular *Transport Operator* and provide them to one or more *MaaS Operators* to be used to create *trips* as pay as go or *mobilityPackages* to be used by a *Traveler*. In Table 3.6 the role is described in more depth.

Table 3.5: Schema for TransportServiceProvider

Role Schema: TransportServiceProvider

Description:

The TransportServiceProvider may have a fixed route for transportation or receive requests from MaaSOperator to transport a particular *Traveler* that made an on-demand request for travel.

Protocols and Activities:

MoveToNextStop, AwaitTransportRequest, TransportTraveler

Permissions:

generates: *transportTimetable*, *vehicle*
reads: *travelDetails*, *travelBill*, *currentCapacity*, *price*, *transportTimetable*, *vehicle*
changes: *price*, *vehicle*

Responsibilities:

Liveness:

FixedRouteTransportProvider = (MoveToNextStop . TransportTraveler)^{W}
OnDemandTransportProvider = (AwaitTranportRequest . TransportTraveler)*

Safety:

$number\_of\_vehicles > 0$
$currentCapacity\_of\_vehicle > 0$

Table 3.6: Schema for TransportTimetableGenerator

Role Schema: TransportTimetableGenerator

Description:

This role is responsible for generating the *transportTimetables* to the *Transport Operators*.

Protocols and Activities:

GenerateTimetable, ProvideTimetable

Permissions:

generates: *transportTimetable*
reads: *transportTimetable*, *vehicle*, *stopsAndStations*, *transportNetwork*
changes: *transportTimetable*

Responsibilities:

Liveness:

TransportTimetableGenerator = (GenerateTimetable)*
ProvideTransportTimetable = (ProvideTimetable)*

Safety:

$number\_of\_vehicles > 0$

The INTEGRATOR role is responsible for integrating different *Transport Operators* into a *MaaS Operator* to enable the delivering of integrated services to the *Travelers*. As identified in Figure 3.2, the integration is done through a *mobilityContract* provided by the INTEGRATOR to a *Transport Operator* interested in providing its services to the MaaS ecosystem. In order to check the validity of a *Transport Operator* requesting a *mobilityContract*, its *transportOperatorProfile* and fleet of *vehicles* must be validated. In Table 3.7 can be found a more in detail description of the schema for INTEGRATOR role.

The TRIPPLANNER is responsible for generating *trips* according to the *tripRequirements* of the *Travelers*. In Table 3.8 TRIPPLANNER is described. As such, when a *Traveler* needs to travel he/she can access a *MaaS Operator* and then pass the *tripRequirements*. Moreover, the TRIPPLANNER can also generate *mobilityPackages* for *Travelers* that travel more regularly, according to their *tripRequirements* and *travelerProfile* which they can then subscribe by a fee.

The PAYMENTOPERATOR is responsible for accepting the payment of a *trip* or a subscription of a *mobilityPackage* by a *Traveler*. These operations must be processed only if the *Traveler* has enough balance to make the payment. Table 3.9 describes in more depth the role.

Table 3.7: Schema for INTEGRATOR

Role Schema: INTEGRATOR

Description:

This role is responsible for integrating different *Transport Operators* and deliver integrated services to the *Travelers*.

Protocols and Activities:

AwaitIntegrationRequest, CheckTransportOperatorValidity, IntegrateTransportOperator

Permissions:

generates: *mobilityContract*
reads: *mobilityContract*, *transportOperatorProfile*, *vehicle*
updates: *mobilityContract*
deletes: *mobilityContract*

Responsibilities:

Liveness:

INTEGRATOR = (AwaitIntegrationRequest . CheckTransportOperatorValidity . IntegrateTransportOperator)*

Safety:

$number\_of\_vehicles = 0 \Rightarrow mobilityContract = nil$

$transportOperatorProfile = bad \Rightarrow mobilityContract = nil$

The POLICYMAKER role, defined in Table 3.10, specifies the activities related to the regulation of the MaaS ecosystem. The regulation is done through the creation and updating policies which may either have the form of incentives or constraints, depending on the goal pretended.

Table 3.8: Schema for TripPlanner

Role Schema: TripPlanner

Description:

Receives request to generate a *trip* or a *mobilityPackage* according to the origin and destination requirements from a Traveler.

Protocols and Activities:

AwaitRequestTrip, AwaitRequestMobilityPackage, GenerateTrip, GenerateMobilityPackage, CreateBill

Permissions:

generates: *trips*, *mobilityPackage*

reads: *travelerInformation*, *vehicles*, *transportTimetable*, *transportNetwork*, *stopsAndStations*

Responsibilities:

Liveness:

TripPlanner = (AwaitRequestTrip, GenerateTrip, CreateBill)^{W}

MobilePackageGenerator = (AwaitRequestMobilitPackage, GenerateMobilityPackage, CreateBill)^{W}

Safety:

$number\_of\_vehicles > 0$

$currentCapacity\_of\_vehicles > 0$

Regarding the TransportNetworkPlanner role, we can say that there is a dependency relation between the TripPlanner, TransportTimetableGenerator and TransportNetworkPlanner roles. The TransportNetworkPlanner role is responsible for generating and updating the *transportNetwork* and *stopsAndStations* according to the needs of the system. These resources are then provided to the agents with the TransportTimetableGenerator role in order to generate the *transportTimetables* with with the routes to be used. Finally this resource is provided to the TripPlanner, together with *transportNetwork* and *stopsAndStations*, ti be used as resources to generate both *trips* and *mobilityPackages*, according to the*tripRequirements* of the Traveler. The complete definition of the role can be found in Table 3.11.

The PolicyMaker and TransportNetworkPlanner together will be responsible for keeping a balance between supply and demand, in a way that the total utility of the system is optimal or near optimal.

Table 3.9: Schema for PAYMENTOPERATOR

Role Schema: PAYMENTOPERATOR

Description:

Responsible for accepting the payment of *trips* or subscription of *mobility packages*.

Protocols and Activities:

AcceptTripPayment, AcceptMobilityPackageSubscription

Permissions:

reads: *travelerInformation*, *trips*, *mobilityPackages*
updates: *trips*, *mobilityPackages*

Responsibilities:

Liveness:

PAYMENTOPERATOR = $(\text{AcceptTripPayment})^{W} \mid\mid (\text{AcceptMobilityPackageSubscription})^{W}$

Safety:

$credit\_information\_travelerProfile = good$
$balance\_of\_travelerProfile - bill\_trip > 0$
$balance\_of\_travelerProfile - bill\_mobilityPackage > 0$

Table 3.10: Schema for PolicyMaker

Role Schema: PolicyMaker

Description:

Create policies and regulation for the MaaS ecosystem

Protocols and Activities:

CreatePolicy, UpdatePolicy, DeletePolicy

Permissions:

generates: *policies*
reads: *policies*, *transportOperatorInformation*, *transportNetwork*, *stopsAndStations*
changes: *policies*

Responsibilities:

Liveness:

PolicyMaker = (CreatePolicy)* || (UpdatePolicy)* || (DeletePolicy)*

Safety:

true

Table 3.11: Schema for TransportNetworkPlanner

Role Schema: TransportNetworkPlanner

Description:

Manages the *transportNetwork* and as well stops and stations in MaaS ecosystem.

Protocols and Activities:

CreateStop, UpdateStop, DeleteStop, UpdateNetwork

Permissions:

generates: *stopsAndStations*
reads: *stopsAndStation*, *transportNetwork*
changes: *stopsAndStation*, *transportNetwork*

Responsibilities:

Liveness:

StopdAndStationsPlanner = (CreateStop)* || (UpdateStop)* || (DeleteStop)*
NetworkPlanner = (UpdateNetwork)*

Safety:

true

3.1.3 Detailed Design

The detailed design phase allows to define the complete system through the agent Model and the service Model. Although Gaia does not deal directly with implementation issues [CO06], these models may act as guidelines for the actual implementation of the agents and their respective activities [ZJW03]. The Table 3.12 describes the instance qualifiers associated with whis phase.

Table 3.12: Instance Qualifiers

Qualifier	*Meaning*
n	there will be exactly n instances
$m..n$	there will be between m and n instances
$*$	x there will be 0 or more instances
$+$	x there will be 1 or more instances

3.1.3.1 Agent Model

In Gaia, an agent class is an entity that may play one or more roles defined in the Role Model. Therefore, in the Agent Model the roles associated with each agent class as well as the cardinality of each of them must be specified. In Table 3.13 the agent classes of the model are defined.

There may be one or more instances of all agent classes, except for `Authority` which is considered to play a more centric role, as the regulator of the system. Regarding the `MaaSOperator`, the possibility to exist more than one instance of this agent class allows the simulation of different levels of MaaS integration. As such, this has particular interest when testing policies and several regulation approaches to MaaS as this allows to a directly compare this different levels of integration.

3.1.3.2 Services Model

The Gaia services model helps to identify services associated with each of the roles played by the agent classes. The services are derived from the activities, protocols, liveness and responsibilities of the roles an agent implements. For each implemented service the *inputs, outputs, pre-conditions* and *post-conditions* must be specified. Inputs and outputs may be derived both from the protocols and the environmental models whether involving either the generation and/or data exchange between agents, or the modification of environmental resources. The pre-conditions and post-conditions represent constraints on the execution and completion of services, being derived from the safety properties of a role or from the organizational rules [ZJW03].

In Table 3.14 we describe the `Traveler`'s Service Model. Based in the TRAVELER role, seven distinct services can be identified. The service "Generate Traveler Profile" is responsible for creating a profile with the *traveler* details. It takes as input the *travelerDetails* and returns the *travelerProfile* as output. There is no associated pre-condition, but there is as post-condition that a *travelerProfile* is created and associated with the respective *traveler*. The next service is

Table 3.13: Agent Model

Agent classes/roles
`Traveler`$^{1..n}$ *play* TRAVELER This means that agent class `Traveler` will be defined to play role TRAVELER, and that we will have between one and *n* instances of this class in the MAS. `TransportOperator`$^{1..n}$ *play* TRANSPORTSERVICEPROVIDER and TRANSPORTTIMETABLEGENERATOR This means that agent class `TransportOperator` will be defined to play the roles TRANSPORTSERVICEPROVIDER and TRANSPORTTIMETABLEGENERATOR, and that we will have between one and *n* instances of this class in the MAS. `MaaSOperator`$^{1..n}$ *play* INTEGRATOR, TRIPPLANNER and PAYMENTOPERATOR This means that agent class `MaaSOperator` will be defined to play the roles INTEGRATOR, TRIPPLANNER and PAYMENTOPERATOR, and that we will have between one and *n* instances of this class in the MAS. `Authority`^{1} *play* POLICYMAKER and TRANSPORTNETWORKPLANNER This means that agent class `Authority` will be defined to play the roles POLICYMAKER and TRANSPORTNETWORKPLANNER, and that we will have one *n* instance of this class in the MAS.

Generate Travel Requirements which is responsible for handling the creation of the travel requirements and details whenever a *traveler* wants to travel. It takes as input the *travelerProfile* of the *traveler* and returns as output the *tripRequirements*. There is no associated pre-condition, but there is as post-condition that a *tripRequirements* is created and associated with the respective *traveler*. The service *Make Request for Travel* handles the request to the *MaaS Operator* to generate *trips* and *mobilityPackages* according to the *tripRequirements* of the *traveler*. This service takes as input the *tripRequirements* and has not an output. On the other hand, as pre-condition the *traveler* must have valid and not null *tripRequirements* and as post-conditions some *trips* or *mobilityPackages* must have been created according to the *tripRequirements*. The *Select Generated Trip* and *Select Mobility Package* services are responsible for the selection by the *traveler* of a *trip* or *mobilityPackage* respectively. Both services takes as input the *tripRequirements* and returns as output the *selected_trip* or *selected_mobilityPackage*. These services have not pre-conditions and as post-condition must have a selected *trip* or selected *mobilityPackage*. The services *Pay Bill* and *Pay Subscription* handles to payment of a *trip* or a subscription of a*mobilityPackage*. These services have as pre-conditions that the *traveler_money* is higher or equal to the *trip_price* or *subscription_price* and as post-conditions that the *traveler_money* has *not-negative* value after the respective operation is completed.

The `TransportOperator`'s Service Model is presented in Table 3.15. It has five services and they are derived from the TRANSPORTSERVICEPROVIDER and TRANSPORTTIMETABLEGENERATOR roles. The service *Await Transport Request* is reponsible for receiving any transport requests from a *MaaS Operator* to transport a *traveler* from an origin to a destination. This service receives as inputs the *travelerProfile* of the *traveler* to transport and the specified *trip* requested by the *traveler* and has not output, pre-conditions or post-conditions. The *Transport Traveler* service is responsible for transporting a *traveler* according to the *trip* details. It receives as input the *travelerprofile* and *trip* and does not return any output. As pre-condition, the *traveler* must be located at the origin of *trip* and as post-condition the *traveler* must be at the destination. The next service is *Move to next Stop* which is responsible for moving a *vehicle* from a *Transport Operator* from a *stop* or *station* to the next one of the route, which may be fixed or dynamic. As pre-condition, the number of remaining *stops* or *stations* of the route must be higher than zero, unless it is the last *stop* or *station*. Moreover, the next *stop* must be different from the last. As post-conditions, the number remaining *stops* or *stations* must be greater or equals to zero and the current *stop* or *station* must belong to the predefined route. The *Generate Timetable* service handles the creation of timetables of the *Transport Operator*. This service takes as input the *stopsAndStations*, *transportNetwork* and available *vehicles* of the *Transport Operator* and returns as output the *transportTimetable*. As pre-condition, the number of available *vehicles* must be greater than zero and as post-conditions must have a *transportTimetable* created and associated to the *Transport Operator*. With the *transportTimetable* generated is possible to provide it to the *MaaS Operators* with who the *Transport Operator* has a *mobilityContract*. It takes as input the *MaaS Operators* and returns as output the *transportTimetable*. The service has not any post-conditions, but as pre-condition the *Transport Operator* must have a *transportTimetable*.

In Table 3.16 we describe the `MaaSOperator`'s Service Model. This model has ten servics and they are derived from the Integrator, TripPlanner and PaymentOperator roles. The service *Await Integration Request* is reponsible for receiving request from a *Transport Operator* to be integrated in a *MaaS Operator*. It takes as input the *transportOperatorProfile* and has not output, precondition or post-condition. The *Check Transport Operator Validity* handles the validation of the information regarding the applicant *Transport Operator*. The service takes as input the *transportOperatorProfile* and returns as output the *resultValidation* in the form of a boolean and has not any pre-conditions or post-conditions. The next service is *Integrate Transport Operator* which handles the integration of a *Transport Operator* in a *MaaS Operator*. This service receives as input the *transportOperatorProfile* and returns as output a *mobilityContract* necessary to the *Transport Operator* to be integrated in a *MaaS Operator*. As pre-conditions, the *Transport Operator* must have a valid *transportOperatorProfile* and has not any *mobilityContract* with the *MaaS Operator* with which want to be integrated. As post-condition, must there is a valid *mobilityContract* between the *Transport Operator* and the *MaaS Operator*. The *Await Request Trip* service handle any request from a *Traveler* to travel. It receives as inputs the *travelerProfile* and the *tripRequirements* and has not output. The service has not any post-conditions and as pre-conditions the *traveler* must have a valid *travelerProfile* and *tripRequirements*. The *Generate Trip* and *Generate Mobility Packages* handles the creation of the routes and *trips* taking into account the *tripRequirements* that they receive as input. The output returned will be either *trips* or *mobilityPackages* depending on the called service. As pre-condition, a valid *tripRequirements* must be provided by the *traveler*, while as post-condition a *trip* or *mobilityPackage* must have been created. The *Create Bill* service handle the creation of the *bill* to be paid by the *traveler* for the selected *trip* or *mobilityPackage* created by the *MaaS Operator*. This service takes as input selected selected *trip* or *mobilityPackage* and returns as output the *bill* for the service, and it has not any pre-condition or post-condition. The services *Accept Trip Payment* and *Accept Mobility Package subscription* handles the payment for the service provided by a *MaaS Operator*. These services takes as inputs the *travelerprofile* and the requested service by the *traveler*, either a *trip* or a *mobilityPackage*. As pre-condition, the *traveler* must have enough money to pay for the service and as post-condition, after paying for the service, the *traveler* must not have a negative balance.

Lastly, the description of the `Authority`'s Service Model can be found in Table 3.17. It has seven services and they are derived from the POLICYMAKER and TRANSPORTNETWORKPLANNER roles. The services *Create Policy*, *Update Policy* and *Delete Policy* are responsible for handle the policies being applied to the environment. The *Create Policy* service has not any input and returns as output a *policy*. It also has not any pre-conditions or post-conditions. The *Update Policy* has as input a *policy* and returns as output an updated *policy*. It has as pre-condition that the *policy* of the input is valid and has not any post-condition. The *Delete Policy* has as input a *policy* and does not return any output. It has as pre-condition that the *policy* received through the input is valid and as post-condition that the *policy* received is deleted. The *Create Stop*, *Update Stop* and *Delete Stop* handle the creation, update and deletion of the *stopsAndStations*. The *Create Stop* has not any input and returns as output a new *stop*, while not having any pre-conditions or post-conditions. On the other hand, the *Update Stop* receives as input a *stop* and returns as output an updated *stop*. As pre-condition, the received *stop* must be valid and has not any post-condition. The *Delete Stop* service receives as input a *stop* and has not any output. As pre-condition, a valid *stop* must be provided and as post-condition, the provided *stop* must have been deleted. Finally, the *Update Network* service is responsible for handling the networks of roads and links of the system and update it whenever appropriated. As input, this service receives the *transportNetwork* and as output an updated *transportNetwork* is returned. As pre-condition, the provided *transportNetwork* must be valid and it has not any post-condition.

Table 3.14: The `Traveler`'s Service Model

Service	Input	Output	Pre-condition	Post-condition
Generate Traveler Profile	*travelerDetails*	*travelerRequirements*	true	$travelerProfile \neq nil$
Generate Trip Requirements	*travelerProfile*	*tripRequirements*	true	$tripRequirements \neq nil$
Make Request For Travel	*tripRequirements*		$tripRequirements \neq nil$	$number\_of\_trips > 0 \vee number\_of\_mobilityPackages > 0$
Select Generated Trip	*tripRequirements*, *trips*	$selected\_trip$	true	$selected\_trip \neq nil$
Select Mobility Package	*tripRequirements*, *mobilityPackages*	$selected\_mobilityPackage$	true	$selected\_mobilityPOackage \neq nil$
Pay Bill	*trip*, $trip\_price$		$traveler\_money \geq trip\_price$	$traveler\_money - trip\_price \geq 0$
Pay Subscription	*mobilityPackage*, $subscription\_price$		$traveler\_money \geq subscription\_price$	$traveler\_money - subscription\_price \geq 0$

Table 3.15: The `TransportOperator`'s Service Model

Service	Input	Output	Pre-condition	Post-condition
Await Transport Request	*travelerProfile*, *trip*		true	true
Transport Traveler	*travelerProfile*, *trip*		$traveler\_at\_origin$	$traveler\_at\_destination$
Move to next Stop	*trip*, *stopsAndStations*		$remaining\_stops > 0 \land next\_stop \neq previous\_stops$	$remaining\_of\_stops \geq 0 \land current\_stop \in trip\_stops$
Generate Timetable	*stopsAndStations*, *transportNetwork*, *vehicles*	*transportTimetable*	$number\_of\_vehicles > 0$	$transportTimetable \neq nil$
Provide Timetable	*MaaS Operators*	*transportTimetable*	$transportTimetable \neq nil$	true

Table 3.16: The `MaaSOperator`'s Service Model

Service	Input	Output	Pre-condition	Post-condition
Await Integration Request	*transportOperatorProfile*		true	true
Check Transport Operator Validity	*transportOperatorProfile*	*resultValidation*	true	true
Integrate Transport Operator	*transportOperatorProfile*	*mobilityContract*	$transportOperatorProfile = ok \wedge mobilityContract = nil$	$mobilityContract \neq nil$
Await Request Trip	*travelerProfile*, *tripRequirements*		$travelerProfile \neq nil \wedge tripRequirements \neq nil$	true
Await Request Mobility Package	*travelerProfile*, *tripRequirements*		$travelerProfile \neq nil \wedge tripRequirements \neq nil$	true
Generate Trip	*tripRequirements*	*trips*	$tripRequirements \neq nil$	$trip \neq nil$
Generate Mobility Package	*tripRequirements*	*mobilityPackages*	$tripRequirements \neq nil$	$mobilityPackage \neq nil$
Create Bill	$trip \vee mobilityPackage$	*bill*	true	true
Accept Trip Payment	*travelerProfile*, *trip*		$traveler\_money \geq trip\_price$	$traveler\_money - trip\_price \geq 0$
Accept Mobility Package Subscription	*travelerProfile*, *mobilityPackage*		$traveler\_money \geq trip\_price$	$traveler\_money - mobilityPackage\_price \geq 0$

Table 3.17: The `Authority`'s Service Model

Service	Input	Output	Pre-condition	Post-condition
Create Policy		*policy*	true	true
Update Policy	*policy*	*policy*	$policy \neq nil$	true
Delete Policy	*policy*		$policy \neq nil$	$policy = nil$
Create Stop		*stop*	true	true
Update Stop	*stop*	*stop*	$stop \neq nil$	true
Delete Stop	*stop*		$stop \neq nil$	$stop = nil$
Update Network	*transportNetwork*	*transportNetwork*	$transportNetwork \neq nil$	true

3.1.4 Behavioral Model

IODA approach ensures modularity in a MAS through simplification of the design and allowing agent-based simulations to be reused. This can be achieved through a separation of interactions from agents and the declarative parts from the procedural ones [KMP11, BMP14].

The IODA model allows to describe the elements of an interaction-oriented mode and how they are managed and represented [KMP11]. Therefore, in IODA each behaviour is represented by an interaction, or rule, involving two agents, a source performing the interaction and the target undergoing it. Furthermore, IODA approach enables a different perspective in simulation design, as the knowledge is represented in different way from the usual action-centric specification of agents [KMP11]. Kubera *et al.* describes the process that rules the behavior of an agent in the following manner: at each timestep, every agent is asked to act and updates its state; each agent then perceives the set of agent in the neighborhood and determines all the possible interaction with that agents; the agents then select the interaction with the most priority among others and performs it.

In this work we have used an interaction matrix to describe the interactions between agents and then describe each interaction. The first column of the table represents the source agents, while the in first line are the destination agents of the interaction initiated by the source agent. Because some interactions may have not an explicit target (degenerate interactions), they are represented in the matrix by $\emptyset$ as suggested by Kubera *et al.* [KMP11].

Definition 1. An *Interaction i* is a tuple ($Interaction_i$, $d_i = \alpha$, $p_i = \beta$) defined by:

- $Interaction_i$ the name of the interaction;
- $d_i = \alpha$ the *limit* distance α between the source and target at which is possible to the interaction to occur;
- $p_i = \beta$ the *priority* β (integer number) of the interaction compared to the other; the higher the value, the higher the priority.

In case that, among the possible interactions, a source agents has more than one tuple that shares the highest interaction, a policy is used to select the interaction to be initiated. By default, the policy sets a random tuple. In Table 3.18 we can see the interaction matrix for the meta-model of MaaS proposed in this work. This matrix was built using as source data the Gaia models done and described in the previous sections. One example of an interaction described using the interaction matrix of IODA is the interactions between the *Transport Operator*, acting as the source agent, and the *Traveler*, acting as the target agent, defined by the (Transport Traveler, d = 0, p = 30). This tuple says that the name of the interaction is Transport Traveler an the *limit* distance between the source and agent is $+\infty$, as for this interaction we assume that the trigger for the transport of the *Traveler* was the *MaaS Operator* requesting the *Transport Operator* to fulfull the requested service by the *Traveler*. Moreover, this interaction has a priority of 30 (the highest of all interactions with *Transport Operator* as the source agent.

The *Traveler* agent may perform, as source agent, the interaction MAKEREQUESTFORTRAVEL, SELECT with the *MaasOperator* agent, while the interactions *Generate Traveler Profile* and GENERATE TRAVELER REQUIREMENTS have not an explicit target. The next agent *Transport Operator* performs the interactions MOVE TO NEXT STOP and GENERATE TIMETABLE without an explicit target, while the TRANSPORT TRAVELER has as target the *Traveler* agent, and AWAIT TRANSPORT REQUEST and PROVIDE TIMETABLE interactions have as target agent the *MaaS Operator*. The *MaaS operator* agent has the interactions AWAIT INTEGRATION REQUEST and INTEGRATE TRANSPORT OPERATOR with the *Transprot Operator* as target agent. Finally the AUTHORITY agent performs all its interactions without an explicit agent, except the PROVIDE NETWORK which has as target agent the *Transport Operator*.

From the interaction matrix we created new tables where we describe in more detail each of the interaction, specifying the *trigger*, *pre-conditions* and *actions*. The *trigger* is what cause the interaction to initiate, the pre-conditions are the conditions of the agents and environment necessary to the interaction be processed in case that is triggered, and lastly the *actions* is what occurs during the process of the interaction. Each of the tables represents the interactions initiated by a particular source agent with the respective target agents. One example of a description in more detail of an interaction is the Transport Traveler interaction. The trigger of the interaction is that the *Transport Operator* has a trip requested by a *Traveler* to be fulfilled. The *Transport Operator* must have some *vehicle* available to process the interaction, and in case this pre-condition is ensured, the Source moves to the origin point of the *Traveler* that requested the travel. Then, the *Traveler* enters in the *vehicle* of the *Transport Operator* and is transport to the destination point, where he/she exist the *vehicle* and the interaction is completed.

Table 3.18: Interaction Matrix

	$\emptyset$	*Traveler*	*TransportOperator*	*MaaSOperator*	*Authority*
Traveler	(Generate Traveler Profile, $d=+\infty$, $p=20$) (Generate Travel Requirements, $d=+\infty$, $p=10$)			(Make Request For Travel, $d=+\infty$, $p=5$)	
TransportOperator	(Move to next Stop, $d=+\infty$, $p=10$) (Generate Timetable, $d=+\infty$, $p=20$)		(Transport Traveler, $d=+\infty$, $p=30$)	(Await Transport Request, $d=+\infty$, $p=5$) (Provide Timetable, $d=+\infty$, $p=20$)	
MaaSOperator			(Await Integration Request, $d=+\infty$, $p=10$) (Integrate Transport Operator, $d=0$, $p=20$)		
Authority	(Create Policy, $d=+\infty$, $p=5$) (Update Policy, $d=+\infty$, $p=5$) (Delete Policy, $d=+\infty$, $p=5$) (Create Stop, $d=+\infty$, $p=5$) (Update Stop, $d=+\infty$, $p=5$) (Delete Stop, $d=+\infty$, $p=5$)			(Provide Network, $d=+\infty$, $p=5$)	

Table 3.19: Description of the interactions between the source agent `Traveler` and its target(s)

Interaction	Trigger	Pre-conditions	Actions
GENERATE TRAVELER PROFILE	true	¬ Source.hasProfile()	Environment sets *travelerProfile*
GENERATE TRAVEL REQUIREMENTS	Source.wantsTravel()	none	Source set *tripRequirements*
TRANSPORT TRAVELER	Source.wantsTravel()	Source.hasTripRequirements()	Target reads *travelerProfile*(Source); Target reads TripRequirements(Source); Target generates Trips Source selects Trip Source pays Trip

Table 3.20: Description of the interactions between the source agent `TransportOperator` and its target(s)

Interaction	Trigger	Pre-conditions	Actions
Move to next stop	Source.hasTripToFinish()	¬ Source.isRouteFinished()	Source set *travelerProfile*
Generate Timetable	true	¬ Source.hasProfile()	Source set *travelerProfile*
Transport Traveler	Source.hasTrip()	Source.hasVehicleAvailable()	Source moves to Origin(Target); Target enters Vehicle(Source); Source moves to Destination(Target); Target exists Vehicle(Source)
Await Transport Request	Source.hasVehicleAvailable()	Source.hasVehicleAvailable()	Source set *travelerProfile*
Provide Timetable	Source.isTimetableUpdated()	Source.hasTimetable()	Source provides *transportTimetable*

Table 3.21: Description of the interactions between the source agent `MaaSOperator` and its target(s)

Interaction	Trigger	Pre-conditions	Actions
AWAIT REQUEST INTEGRATION	none	none	Source receives request
INTEGRATE TRANSPORT OPERATOR	Source .receivedRequestIntegration()	¬ Source .isTransportOperatorIntegrated(Target)	Source reads *transportOperatorProfile(Target)*; Source generates *mobilityContract*; Target reads *mobilityContract*; Source integrates transportOperatorProfile(Target);

Table 3.22: Description of the interactions between the source agent `Authority` and its target(s)

Interaction	Trigger	Pre-conditions	Actions
CREATE POLICY	Source.wantsCreatePolicy()	none	Source set *policy*
UPDATE POLICY	Source.wantsUpdatePolicy()	Source.hasPolicy()	Source updates *policy*
DELETE POLICY	Source.wantsDeletePolicy()	Source.hasPolicy()	Source deletes *policy*
CREATE STOP	Source.wantsCreateStop()	none)	Source set *stop*
UPDATE STOP	Source.wantsUpdateStop()	Source.hasStop()	Source updates *stop*
DELETE STOP	Source.wantsDeleteStop()	Source.hasStop()	Source deletes *stop*
PROVIDE NETWORK	Source.isNetworkUpdated()	Source.hasNetwork()	Source provides *network*

3.2 Demand Behavioral Modelling

In this section we present the demand modelling proposed in this work to be used in the context of the simulation of MaaS scenarios. We will start with the AT generation using Behavioral Differentiation Model (BDM) in conjunction with the concept of social practices. Following, we present the decision-making process that the artificial society of *travelers* will use during the a particular simulation. Lastly, a mechanism of *self-adaptation* called Clonal Plasticity [NC18] and an an hierarchical Reinforcement Learning will allow the artificial society of commuters created with BDM to grow in its decision process by adopting new behaviours and *self-adapting*, through the simulation, in response to the state changes of the system.

3.2.1 Generation of the Artificial Society

Lacroix and Mathieu propose the BDM as a method to generate of a population of agents through *norms*. The *norms* represent behavioral patterns allowing to capture the behavior of a group of agents. Therefore, BDM allows to automatically infer behaviors from a sample data and use them to model the agents in a simulation [LM12].

On the other hand, the concept of Social Practice Theory (SPT) for agent-based simulation focuses in the attributes of activities, namely related values, activities, agents, resources or locations [MDJ18]. Social practices are defined as accepted ways of doing some action, contextual and materially mediated, that is routinized over time. They can be seen as patterns which can be filled in by a multitude of single and often unique actions [CD19]. The way a social practice is perceived is based on the beliefs related to both the action and the environment where an agent is living. Therefore, in the case of demand modelling in the context of MaaS, there may agents that when traveling consider a good social practice use car, while other agents, based on their beliefs related to pollution or cost of using a car, may consider using a service provided by a MaaS operator a better option.

In our approach, we propose the combination of BDM with the concept of social practices, where, from a sample data, social practices based on the actions, activities and beliefs may be extracted and used to automate the creation of an Artificial Society.

The *behavioral parameters* of the simulation are represented by the *Parameters* in the model.

Definition 1. A *Parameter* p is a tuple $(p_{ref}, \mathscr{D}_p, v_p, g_p, f_p)$ defined by:

- $p_{ref}(p)$ a reference parameter;
- $\mathscr{D}_p$ a finite domain, with if $p_{ref} \neq null$, then $\mathscr{D}_p \subseteq \mathscr{D}_{p_{ref}}$;
- $v_{d_p} \in \mathscr{D}_p$ a default value;
- g_p a probability distribution over $\mathscr{D}_p$, with by default g_p a uniform distribution;
- $f_p : \mathscr{D}_{p_{ref}} \mapsto [0,1]$ a distance function that allows to compute the gap between a value and a p definition domain with by default $\forall x \in \mathscr{D}_{p_{ref}}, f_p(x) = 0$.

The Social Practices specify agent activities, habits and interconnected behaviour between actions. A Root social practice is used to check the conformity of the agents with the specification of the social practice.

Definition 2. A *Social Practice SP* is a set $\{SP_{ref}, \mathscr{P}_{SP}, \mathscr{Q}_{SP}, \tau_{SP}, \delta_{max_{SP}}\}$ defined by:

- $SP_{ref}(SP)$ a reference social practice;
- $\mathscr{P}_S P$ a finite set of parameters p;
- $\mathscr{Q}_S P$ a set of properties;
- τ_{SP} a violation rate of the social practice, which describes the proportion of violating behaviors, with $\tau_{SP} \in [0,1]$. $\tau_{SP} = 0$ is the default value;
- $\delta_{max_{SP}}$ a maximal gap to the social practice, which describes the tolerance towards social practice violations with $\delta_{max_{SP}} \in [0,1]$. $\delta_{max_{SP}} = 1$ is the default value.

The *Model Agents* represent the instantiation of a social practice and the associated *parameters*. Therefore, the *simulation agents* that are created from a particular *model agent* will represent their behaviour and social practice.

Definition 3. A *Model Agent* a_m is a set $SP_{a_m}, \mathscr{C}_{a_m}$ defined by:

- SP_{a_m} a reference social practice;
- $\mathscr{C}_{a_m} = (p, v_p), p \in \mathscr{P}_{SP_{a_m}}$ a set of pairs of parameters and associated value.

Lacroix and Benoit suggest the use of self-organizing maps and distribution function estimation to automate the process of configurating the Model [LM12, T.95]. The number of clusters is dynamically computed and for each of the k clusters, a social practice SP_k representing an inferred cluster and d $parameters_{k,i}$, representing different dimensions of the sample data, are created. The Algorithm 1 describes in more detail each step of this phase.

In the work of Lacroix and Benoit a tool combining profiles, time slices and generators is proposed to populate a database with a population of agents [LM12]. They propose the use of generators as a way to generate the agents of an Artificial Society. In their work, at each timestep each generator is checked to verify if it includes an active time slice. If so, a profile p is randomly selected using a probability pc to balance the choice of the profiles. The percentage of each profile is set at the corresponding proportion of agents matching this norm in the sample data set [LM12].

In our approach, we adapt their method as a generator is used only before starting the simulation, as our intention is to grow and evolve the initial Artificial Society as we describe in Subsection 3.2.3. As such, the definition of *time slice*, proposed by Lacroix and Benoit to allow the generation of different populations at various time frames is not used. Therefore, our propose is a single use of a generator of agents during the setup of the simulation, where each agent of the

Algorithm 1 Automated creation of social practices.

```
Require: a set of inputs $\mathscr{E} = e$ with $d$ dimension of the input vectors $e$
  create the self-organizing map $\mathscr{K}$ of rectangular topology with $k = (d+1)^2$ neurons of weights $W_i = (w_{i,j})(i\ in[1,k]$ and $j \in [1,d]$; train $\mathscr{K}$ with the set of examples $\mathscr{E}$
  for each $i \in [1,k]$ do
      create a $SocialPractice\ SP_i$ such that $Q_{N_i} = \emptyset, \tau_{N_i} = 0, \delta_{max_{N_i}} = 1$, and $N_{ref(N_i)} = N_{root}$
      for each $j \in [1,d]$ do
          create a $Parameter\ p_{i,j}$
          save the weight value $w_{i,j}$ of the neuron $i$ as the default value of $p_{i,j} : v_d(p_{i,j}) \leftarrow w_{i,j}$
      end for
  end for
  for each $e \in \mathscr{E}$ do
      classify the example $e$ using the network $\mathscr{K}$. Let $W_i$ be the weights of the triggered neuron
      for each $j \in [1,d]$ do
          if $w_{i,j}$ is greater than the maximum or lower than the minimum of $\mathscr{D}_{p_{i,j}}$, update the corresponding bound of the domain
          add the value $e_j$ to the distribution estimator of the $Parameterp_{i,j}$
      end for
  end for
```

Artificial Society is automatically created using the BDM and the social practices associated to a profile. The Algorithm 2 describes in more detail the generation of an AT.

The behavioral pattern of the agents is specified by a *Profile* which is associated with a social practice, where a set of properties related to the simulation itself is also described such as the itineraries.

Definition 4. A *Profile p* is defined by:

- SP_p a social practice;
- $\mathscr{Q}_p$ a set of characteristics.

In our approach the *Generator* no longer includes a set of *time slices*, but instead has a set of profiles to be used for the generation of the population of agents.

Algorithm 2 Creation of the agents of the Artificial Society by a generator.

```
Require: $g$ generator
  $\alpha \leftarrow$uniform_random([0,1]); $\beta \leftarrow 0$
  for each $(p, pc) \in \mathscr{P}t$ do
      if $\beta \leq \alpha < \beta + pc$ then                    ▷ select this profile
          generate an agent using the behavioral differentiation model and norm $N_p$
      end if
      $\beta \leftarrow \beta + pc$
  end for
```

Definition 5. A *Generator g* is defined by:

- $\mathscr{P}_t$ a set of profiles associated to the relative percentage of this profile in the population: $\mathscr{P}_t = \{(p, p_c), p \in \mathscr{P}_r, pc \in [0,1]$ and $\sum_{p \in \mathscr{P}_t} pc = 1\}$;

- $f_g : \mathscr{A} \to \Re^3$ a function associating a position in space to an agent.

3.2.2 Decision-making process

In a transport system a *traveler* can move from one point to another through several modes like private car, public transport, taxi, bike among others. In a daily routine basis or just a sporadic travel, whenever a *traveler* want to execute a specific activity outside of his/her home, a choice will have to be made among the available options to travel. The choice will be mostly based on the social practices of *travelers* and in what they believe to be the best option to choose, regardless if in reality it really happens to be as such. Therefore, the social practices and associated beliefs of the *travelers* must have be taken in consideration when modelling a decision-making process of a transport system, as a *traveler* will mostly be deciding based on his / her beliefs and perceived value associated to a choice. If for example a *travelers* whats to execute some activity and believes that the best is to use bus, just because he/she has the habit of using it and believes is a nice mode of travel, there is a higher probability of repeatedly use the same mode of transportation in future travels even there is a better option to take him/her to the same destination [MDJ18].

Nevertheless, mechanisms like Reinforcement Learning based on the maximization of reward accumulated for taken an k action may help to model social practices and hence the decision to be made by a *traveler* in future travels for the same origin-destination (OD) routes. This problematic will be addressed in the next section when we make our proposal regarding the Growing of the Artificial Society of *travelers*. In the context of MaaS we are adding two new decision actions to the *travelers* whenever they want to travel. First, a *traveler* will have as a new mode of traveling the MaaS itself, regardless of plan or mobility packaged selected. Then, in case of choosing to use MaaS to travel, the *traveler* will have to check the trips or mobility packages generated for the OD of the trip requirements of the *traveler* and the choose, among then, what option to go ahead.

Xie *et al.* propose the concept of *informed regular choice* in opposition to a *regular choice* when deciding the mode to use to travel [XDA+19]. As already discussed in the works of Ben-Akiva *et al.* [BABG+07] and Mahmassani and Lin [ML99], Xie *et al.* consider that the real-time information provided by a on-demand app, such as availability of alternatives or travel time and cost estimates, could have an impact in the decision-making on other transport modes. This is related to the fact that the information acquired from simply viewing the options proposed by a MaaS app could influence the decision to be made by a *traveler*, as he/she could do an *informed regular choice*, with information about the expected experience to the *traveler*, instead of a just *regular choice* without any information *a priori* of what a particular trip would look like.

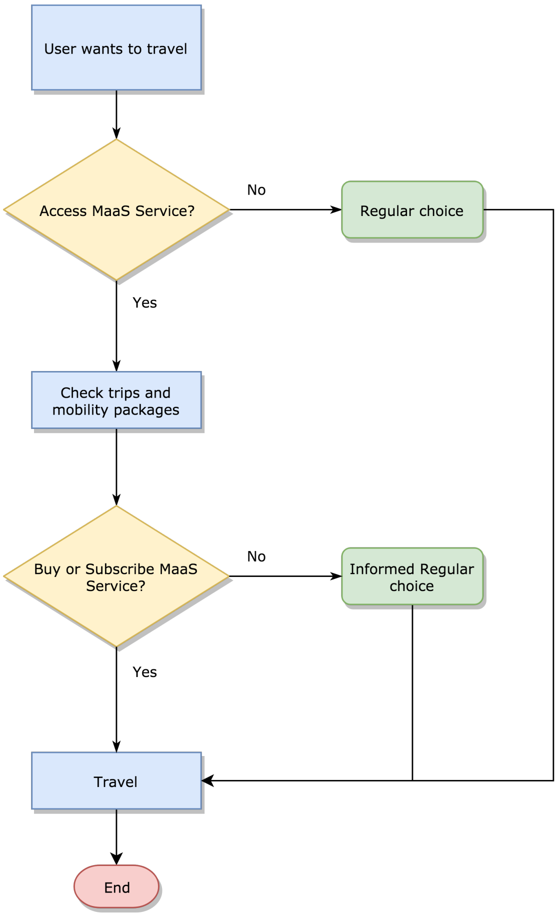


Figure 3.3: Decision-making process in MaaS.

Therefore, as described in Figure 3.3, a *traveler* first needs to decide if wants to to buy or subscribe some MaaS service. In case the *traveler* excludes the usage of MaaS a regular choice is made among the possible modes of transportation available and without any possible useful information to decide the best choice. On the other hand, if the *traveler* decides to access the MaaS app and check the generated trips and mobility packages, according to his/her travel requirements, the *traveler* will get information *a priori* of the current state of the transport system and what could be the best option to choose. The *traveler* then decides if wants to buy or subscribe a MaaS service of instead wants to exit MaaS and make a *regular choice*, which in this case will be an *informed regular choice*.

The *travelers* in our Multi-Agent System are considered to have a selfish intrinsic nature and little to none information about the other pairs in the simulation. As such, when a *traveler* has to make a decision regarding the choice of the transport mode or route to use between and origin and destination (OD), the decision will be taken with little to none communication between the *travelers*. As described by Chiu *et al.*, one common assumption regarding the decision of a route OD is that the choice is made according to the principle of minimum experienced travel time [CYCT10]. When all the *travelers* succeed to choose the optimal route that minimises their travel times an Equilibrium of the system has been reached. One approach to this problem is a self-organizing game called Minority Game (MG), which address situations where coordination between agents must exist through self-organization, even without communication and minimal information. At each timestep, each agent make a choice from some actions and, in the final of the game, the group that is in minority wins a reward. A feedback loop induces the agents to reevaluate their actions at each iteration. In our problem, the *travelers* compete for a limited resource (bus-seat, metro-seat, road, etc) when they have to make a choice firstly between MaaS and a regular choice and then, in case of choosing to use MaaS to travel, when they decide which mobility package to use. Therefore, we can view these two situations as two independent minority games inside the decision-making process of the demand. Because the original MG was designed to be used only for situation where an agent has to make a choice between two options, and because during the decision-making of our MAS may there are more than two option when choosing the optimal route or transport mode, we suggest the use of an extension to the MG concept namely Multi-Choice Minority Game (MCMG). Regarding the MCMG, there at least two different approaches, one using neural networks proposed [EDMKK01], where only one decision strategy is used and can evolve, and the MCMG proposed by Chow *et al.* where more than one strategy can be used but none can evolve like in the original MG [CC03].

3.2.3 Growing of the Artificial Society

Techniques based on the natural process of evolution like Genetic Algorithms or Evolutionary Algorithms use fitness functions in order to generate diversity among the population, through convergence to a good solution [DJ06].

However one of the problems in Evolutionary Computation is the loss of diversity in early generations of the computation, due to premature convergence. Several approaches to address this problem were proposed like the prevention of similar individuals to combine [Deb89], or insertion of random individuals in each generation as a path to slow down convergence and increase diversity of the population[Cob93].

Nallur and Clark proposed *Clonal Plasticity* as a mechanism of self-adaptation and self-diversification which combines two bio-inspired mechanisms: *clonal reproduction* and phenotypic plasticity (typically present in plants) [NC18]. While clonal reproduction refers to the reproduction process where the descendent is genetically similar to the parent, phenotypic plasticity describes the mechanism where structural differences in genetically similar organisms are explained as result a of self-adaption and survival strategy towards the surrounding environment.

These characteristics allow *Clonal Plasticity* to distinguish from Genetic Algorithms or Evolutionary Algorithms, as the genome and functionality of the individuals are not changed. Instead, Clonal Plasticity allow some degree of plasticity for each agent behaviour [NC18]. In Table 3.23 the steps of Clonal Plasticity are described.

Choosing the plasticity range is the cause of generating diversity among the artificial society. During the simulation, at each time-step t, the adaptation decision depends on both the feedback received from the environment, whether positive or negative, and the memory of the modification

Table 3.23: Clonal Plasticity steps (Adapted from Nallur and Clark [NC18])

Step	Description
Identification of plasticity points	Each agent identifies all its parts that can present multiple behaviors.
Evaluation of the environmental input	Environment feedback is evaluated to verify for each plastic point if it needs to adapt a different strategy and behaviour.
Plasticity memory	A record of previous Plasticity Range is maintained in order to allow an agent to return to a previous good strategy of adaptation.
Choice of plasticity range	Plasticity range is calculated based on plasticity memory and reward received in the step by the agent. The response may be of the following: *Exact Clone:* m: ↑ and positive reward *Low Plasticity:* m: ↓ and positive reward *High Plasticity:* m: ↓ and negative reward
Clonage and modification of plastic points	Agents make clone from themselves and are allowed to adapt plastic points to adapt to the environment.

action occurred at time $t-1$. Therefore, depending on these two factors, the agent will choose a plasticity range towards a better adaptation to the environment.

The plasticity range may be of one of the following types:

- *Exact Clone*: the agent makes a copy from itself without any changes;
- *Low Plasticity*: agents chooses the same plastic point from the previous iteration and changes it in the same direction as before;
- *High Plasticity*: agents chooses a different plastic point from the previous iteration and changes it in a random direction.

In case the feedback received is negative, then the plasticity range is *High Plasticity*. In case the feedback from the environment is positive and the memory from the previous action is also positive, then the plasticity range is *Exact Clone*. Finally, if the feedback received from the environment is also positive, but the memory from the previous action is negative, then the plasticity range chosen is *Low Plasticity* [NC18]. The Algorithm 3 and Algorithm 4 show in more detail how to create a clone from an agent and choose the plasticity range at each iteration.

Algorithm 3 Creation of a clone.

```
Require: PlasticSet, Memory, LastReward
for each Agent a do
    $LastReward_a \leftarrow$ EvalEnviron($a, PlasticSet_a$)
    $WhichRange_a \leftarrow$ ChoosePlasticityRange($LastReward_a, Memory_a$)
    switch $WhichRange_a$ do
        case Exact-Clone do
            clone ← a
            return clone
        case Low-Plastic-Clone do
            clone ← a
            plasticity-point, direction ← $Memory_a$
            ModifyAgent(clone, plasticity-point, direction)
            return clone
        case High-Plastic-Clone do
            clone ← a
            last-plasticity-point, last-direction ← $Memory_a$
            plasticity-point, direction ← $Memory_a$
            direction ← $chooseDifferent(last - direction)$
            ModifyAgent(clone, plasticity-point, direction)
            return clone
end for
```

Because every action and adaptation has a cost for the system, either computational or communicative, the concept of Cloning Frequency. This notion refers to the time-period between *self-evaluation* of the agents. As such, Clonal Plasticity may not happen at every time step, but at a frequency that is considered feasible and appropriate to the characteristics of the simulation.

Algorithm 4 Choosing of the plasticity range.

```
Require: Memory, LastReward
if $LastReward < 0$ then
    return Low-Plasticiy-Clone
else
    if $Memory > 0$ then
        return Exact-Clone
    else
        return High-Plastic-Clone
    end if
end if
```

In this chapter we propose the use of the Clonal Plasticity mechanism to address the generation of population diversity as a way to provide growing behavior and adaptation to the inputs received from the environment. Therefore, the artificial society generated using Behavior Differentiation Modelling will be able to change and adapt their behavior according to the conditions of system. This will enable the agents to make different choices regarding destination, mode of transportation, start and arrive time and evolve in a smoother way compared to Evolution Computation [NC18]. In Figure 3.4 we describe how we intend to use it during the simulation.

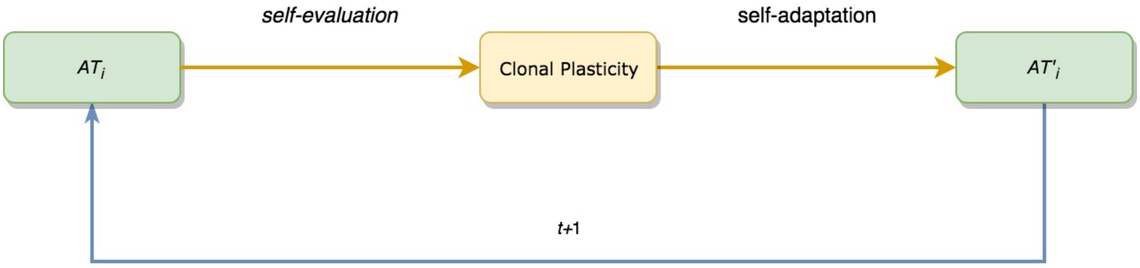


Figure 3.4: Mechanism of growing of the *travelers* through *self-adaptation*

At each timestep, each agent of the artificial society AT_i, which represents a *traveler*, reads the inputs of the environment and makes a *self-evaluation* in order to determine the degree of adaptation to the current conditions of the environment. Following that, the mechanism of Clonal Plasticity is processed taking as possible plasticity points the travel preferences and social practices specifics to each *traveler*. When the *self-evaluation* is finished, each *traveler* proceeds to a *self-adaptation* resulting in a new derived artificial society AT_i'. Furthermore, $t+1$ refers to the next time-step when may occur a new cloning process, which depends on the cloning frequency. This allows the introduction of *cloning frequency* as a way to allow the *self-adaptation* taken by each *traveler* in time-step t to take effect and be properly evaluated before the next iteration begins [NC18].

In order to complement the Clonal Plasticity in the process of growth and evolution of the Artificial Society of *travelers*, we suggest the use of techniques such as Reinforcement Learning (RL). This mechanism is concerned with how the agents may maximise their cumulative reward depending on the actions they take. Roth and Erev proposed an algorithm that allow to model the performance of multiple strategic players in a competitive game, where each agent tries to learn the optimal action to take based on a succession of action-reward pairs [RE95]. The algorithm specifies initial propensities q_0 for each of N actions possible and based on reward r_k for action a_k the propensities at time $t+1$ are defined as:

$$q_j(t+1) = (1-\phi)q_j(t) + E_j(\varepsilon, N, t, k) \tag{3.1}$$

$$E_j(\varepsilon, N, t, k) = \begin{cases} r_k(t)[1-\varepsilon] & \text{if } j = k \\ r_k(t)\frac{\varepsilon}{N-1} & \text{if } j \neq k \end{cases} \tag{3.2}$$

Where:

- $q_j(0)$ initial propensity of action k at time $t = 0$;
- $q_j(t)$ propensity of action k at time t;
- $r_k(t)$ reward for taking action k at time t;
- ϕ recency ("forgetting") parameter;
- ε exploration parameter;
- N number of actions.

Probability of choosing action j at time (t) is given by:

$$P_j(t) = \frac{q_j(t)}{\sum_{n=1}^{N}[q_n(t)]} \tag{3.3}$$

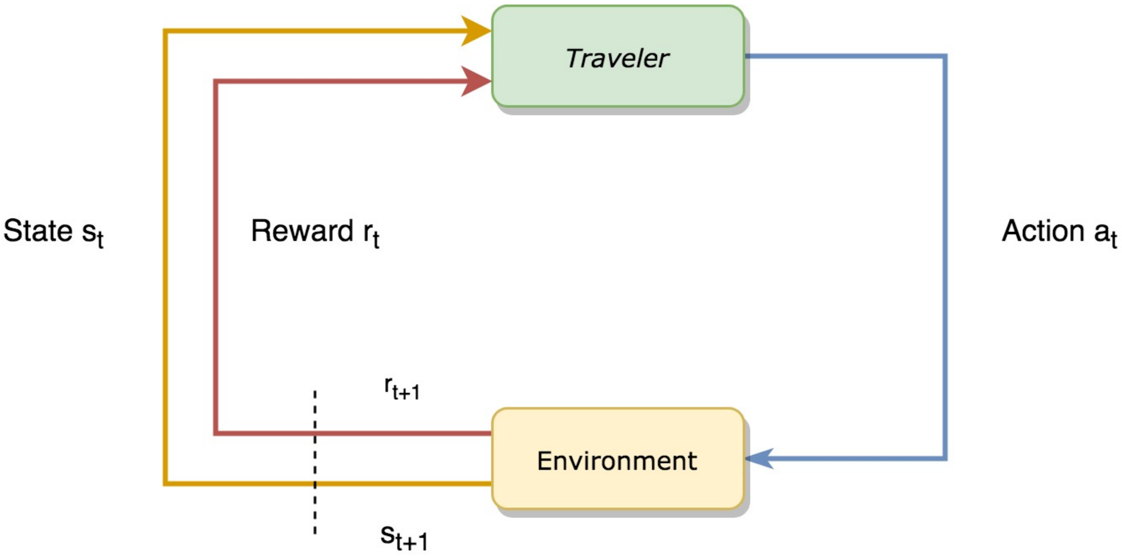


Figure 3.5: Reinforcement learning of *Travelers*

In the case of our model, RL is used either to apply the reward to the agents that win the minority game, but also in the process of learning itself, implemented by the *travelers*. Because we use two independent minority games, one to choose a mode of transportation and another to choose a mobility package provided by a MaaS Operator, we also use two different sets of variables for the RL algorithm. The propensities, if seen as the belief or habit of using a particular mode of transportation, they are the metaphor of social practices in our modal, where each social practice (propensity) may evolve and *self-adapt* depending on the operational policies, incentives, and constraints applied to the model, until an equilibrium is reached. On the other hand, Clonal Plasticity may be applied directly to the strategy of learning (RL) itself, cloning the recency parameter and exploration parameter. Other characteristics of the agents and/or their strategies may be used in the growing process of the agent, as long as a change in their value may have an impact on the decision-making process of the agent.

3.3 Chapter Summary

In this chapter we have made a description of the proposed meta-model to describe MaaS and how we intend to model the demand during a simulation. As described, we intend that the Artificial Society of *travelers* is able to be both generated automatically from a sample data and from there grow and *self-adapt* to the inputs that received from the environment, which will have an impact on the decision-making process of each agent.

Chapter 4

A proof-of-concept MaaS instantiation

In this chapter, we present the results of the experiments regarding the proposed meta-model for MaaS and related methodology for the Demand Behaviour Modelling described in Chapter 3. We instantiated the proposed meta-model, and then conducted several experiments with different monetary policies to evaluate the influence of certain parameters in the system, in particular in the behaviour of each *traveler* that forms the artificial society. As a proof-of-concept for the proposed meta-model, we have focused in this experiment mainly in the growing of the behaviour of the demand, creating the basis for a future tool of evaluation of transport systems with focus in MaaS.

4.1 Experimental Design

In this section, both methodological aspects and theoretical aspects of the implementation level of the experimental design are described. We will start by presenting the approach to the traffic simulation of the experiment and then discuss the details of the travelers artificial society and transportation network.

4.1.1 Traffic Simulation

The models for traffic simulation may either be classified as microscopic or macroscopic. A microscopic simulation is recommended for observing the behaviour of a particular vehicle, as the traffic cannot be seen as a purely mechanical system. As such, the traffic simulation must take in consideration the capabilities of real human drivers, like intention, perception or driving attitudes. Furthermore, a macroscopic modelling approach is normally used to model the traffic flow, as this kind of approach can make statements of the global qualities of traffic flow [KMR+14].

We consider the traffic simulation as an integration of a macroscopic representation of a transportation network and the microscopic representation of an artificial society of *travelers*, each one having its own decision-making process and perception of the environment. The introduction of modifications in a traffic simulation, either as direct or indirect actions by the authorities, may influence the behaviour of the *travelers*. This is intentional, as it pretends to align the objectives and preferences of the *travelers* to the ones of the system.

The simulation was designed as a simple scenario where each *traveler* has the ability to make decision over the mode or service to use for transportation, according to their social practices and perception of the environment. In case of car ownership, the *travelers* that own a car, can either opt for using their own car, or use a mobility package of transportation provided by the MaaS operator of the system as a service. The simulation was implemented in the NetLogo multi-agent programmable modeling environment [U.99].

4.1.2 *Traveler* Artificial Society

The artificial society of the system is represented by the *travelers*, modelled according to their travel preferences. Each *traveler* is characterized by a set of attributes regarding their travel preferences, such as socioeconomic features (e.g., income), and in terms of costs (e.g., waiting time cost, car cost if owner of any, public transportation fares) and time (e.g., desired travel duration, desired arrival time). The artificial society is generated as described in Section 3.2, with their travel experiences and Each has an activity-based schedule representing their preferences and constraints. Moreover, the schedule also defines the set of origins and destinations for each activity, detailing respective desired departure and arrival times to and from each node.

The decisions made by each *traveler* are based in a utility-based approach, where a *traveler* makes an evaluation of his/her travel experience. Therefore, the *travelers* will learn from their past experiences and leading to a learning of the rules of the system. The total utility of a *traveler* j can be calculated as the sum of different individual utility contributions, as shown in Equation 4.1.

$$U^j_{total} = \sum_{i=1}^{n} U^j_{perf,i} + \sum_{i=1}^{n} U^j_{time,i} + \sum_{i=1}^{n} U^j_{cost,i} \tag{4.1}$$

Where $U^j_{perf,i}$ is the utility perceived for performing an activity i, $U^j_{time,i}$ is the (negative) utility as time, such waiting and travel time for an activity i and $U^j_{cost,i}$ is the perceived utility cost for traveling during trip i. Furthermore, n represents the number of activities, which is equal to the number of trips, with first and last activities being counted as one. At the end of the travel, each agent memorizes the experienced travel time and costs. These variables will be used to calculate following day's utility. After that each agent evaluates its own experience, comparing the expected utility to the effective utility.

Based on the minority game concept, we considered the number of commuters on each road and type of transportation, and according to the Roth-Erev's learning model, reward was assigned to winner who is in minority number and follows the criteria below:

$$U_{effective} > U_N, \text{ with } U_N = \frac{1}{N}\sum_{j=1}^{N} U^j_{effective} \tag{4.2}$$

4.1.3 *Transport Operators*

The *transport operators* are responsible for transporting the *travelers* from one origin point to the destination, according to the trip requirements of the *traveler*. On the other hand, different transport modes may lead the *travelers* to different experience usage experiences. Several attributes may contribute to this such as the travel cost, travel time, waiting time, late time of the travel, or crowdedness of the vehicle (applicable to the PT). Therefore, the choose of the *transport operator* will have an impact in the utility perceived by each *traveler*.

For ths proof-of-concept, we will be using as available transport modes the private car, bus, metro and robotaxi.

4.1.4 *MaaS Operator*

The *MaaS Operator* is the stakeholder of the ecosystem responsible for enabling MaaS itself. Therefore, it integrates several *transport operators* within the environment, and working as a broker, it does mobility aggregation of the transport modes available, according to their timetable and capacity, and created *trips* and *mobility packages* ready to be consumed by a *traveler*, according to his/her *trip requirements*.

The simulation model will be considered a MaaS directed to urban areas and, as such, we will be considering some public transport modes, namely bus and metro, and also robotaxis, where more than one *traveler* will be allowed to use the same vehicle. With these transport modes, the *MaaS Operator* creates two different mobility package to the *travelers* that choose to travel using MaaS: one combining bus and metro and another combining metro and robotaxis.

4.1.5 *Authority*

In Section 3.1.2 we described the *Authority* stakeholder and its associated roles, as the member of the ecosystem of MaaS responsible for regulating the transport system. As such, they do this task by implementing or updating operation policies and incentives that aim to achieve an improvement in all the system.

Therefore, as a a proof-of-concept, we model the *Authority* stakeholder by applied different policies to the system in order to evaluate how the rest of the stakeholders, and environment itself, react to the changes.

4.1.6 Transportation network

A transportation network can be formally modelled as a graph *G(V, L)*, with *V* representing a set of nodes including origins, destinations, intersections, and *L* defining a set of roads (edges or directed links) between nodes [KLBE17, KMR+14]. Each link $l_k \in L$ has some attributes such as length, mode of transportation and capacity. Furthermore, to represent the congestion effects in the links, a volume-delay function is represented in Equation 4.3, allowing to evaluate macroscopically how the exceeding the capacity of the flow of a link affects the time and speed of travel [dDOJL11].

$$t_k = t_{0k}[1+\alpha(\frac{X_k}{C_k})^{\beta}] \tag{4.3}$$

Where t_{0k} is the free flow travel time, X_k is the number of vehicles, and C_k represents the capacity of the link k. In this equation, α and β are controlling parameters.

The scenario of the simulation consists of a multimodal network with one origin O and one destination D. Each link l of the network is described by a length l_l (in kilometers) and by a capacity c_l (in vehicles/hour). For simplicity purposes, each link is one-way and represent a single option of transportation of the *traveler*. The origin-destination matrix is presented in Figure 4.1.

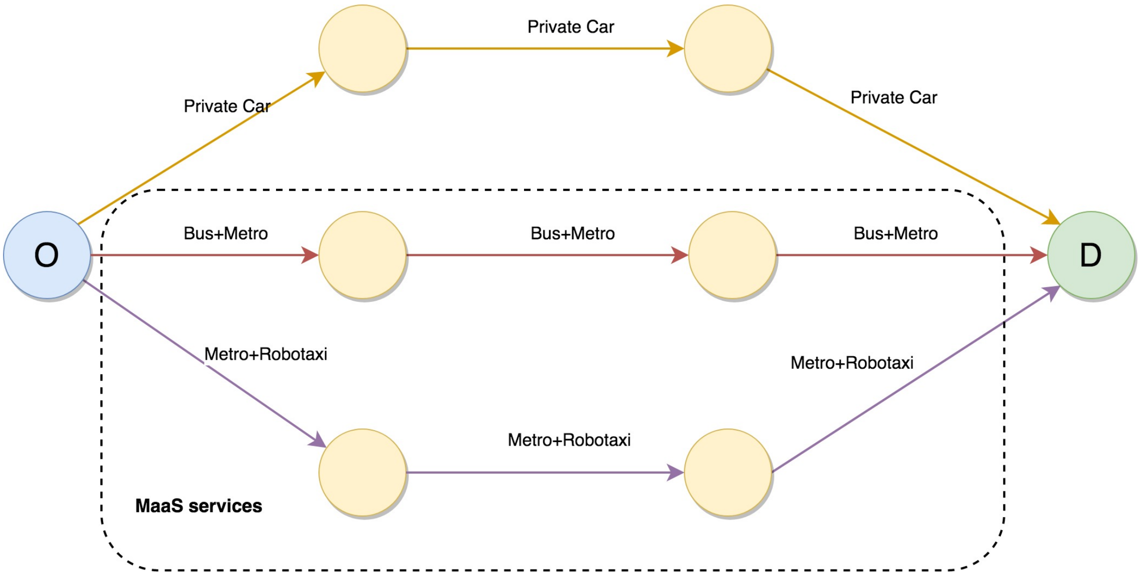


Figure 4.1: Origin-Destination matrix of the simulation

The agents of the artificial society, represented by the *travelers*, may opt between using a single mode of transportation or a combination of several different modes of transportation bundled as a package and provided to the *traveler* as a service ready to be consumed.

4.1.7 Initial Setup

A population consisting of 1001 commuters was created, with an odd number in order to work with the concept of Minority Games. They were characterized by the number of attributes such as departure and arrival times, mode and daily income. Car-ownership is a Boolean variable and indicates whether the agent is a private or a public transportation user. All plans of the *travelers* were performed in rush hours of the day from 6:30 am to 10:30 am, with a normal distribution to simulate peak times. It was observed a high demand in peak duration between 8-9:30 am, on both roads. The range of income was 30 to 80 Euro per day. The routes between nodes Origin and Destination had both a length of 19 km. The public transportation frequency service was 10 minutes before the rush hour and 5 minutes during the rush hour. In Table 4.1 we can see the default values used for the simulation.

Table 4.1: Default Values of the Simulation

Variable	Value
Number of travelers	N = 1001
Capacity of links	L = 150
Capacity of bus	B = 70
Capacity of metro	M = 200
Capacity of robotaxi	RT = 5
Cost of Private Car	0.11 €/km
Cost of Bus	0.25 €/km
Cost of MaaS-Bus-Metro	0.25 €/km
Cost of MaaS-Bus-Robotaxi	0.30 €/km
Traveler's income	30 to 80 €/day
Simulation period	365 days
Time	6:30 am to 10:30 am
Initial ϕ (recency)	0.25
Initial ε (forgetting parameter)	0.25
Cloning Frequency	5 days

4.2 Experiments and Results

We have performed 3 different simulations, each with 60 iterations and with different mobility options for the *travelers*. The first had as options private car and bus, the next private car and MaaS and finally, again private car and MaaS, but with a policy that increased the cost of using private car. Both Clonal Plasticity and Roth's and Erev's algorithm were used to evaluate these concepts could could influence the decision-making of each *traveler*, as the growing and *self-adaptation* could lead to a different choice regarding the transport mode, depending on the inputs received from the environment and in what direction the *self-adaptation* could move as an answer.

During the simulation's steps, we have monitored several parameters of the *travelers*, namely the expected and effective utilities, average travel times of each transport mode, number of commuters on each mode and also the variation of the learning parameters related to Roth's and Erev's algorithm.

In Figure 4.2 we can see the variation of the number of *travelers* per transport mode for the simulation with the transport modes private car and and the ones provided by the *MaaS Operator*. From the analysis of the chart, a balance between the *travelers* that choose to travel using private car and the one that choose a MaaS service can be seen. This is in agreement with the values displayed in Figure 4.3, where the variation of the utility is evaluated, and Figure 4.4, where the propensities are depicted and, as expected from the results extracted from Figure 4.2, the propensities to choose private car or a MaaS service are identical. As such, the agent *traveler* perceive these two social practices with similar beliefs on what they represent to him/her. Furthermore, the values of the propensity for the different transport modes fluctuate during the simulations as the result of Roth's and Erev's learning.

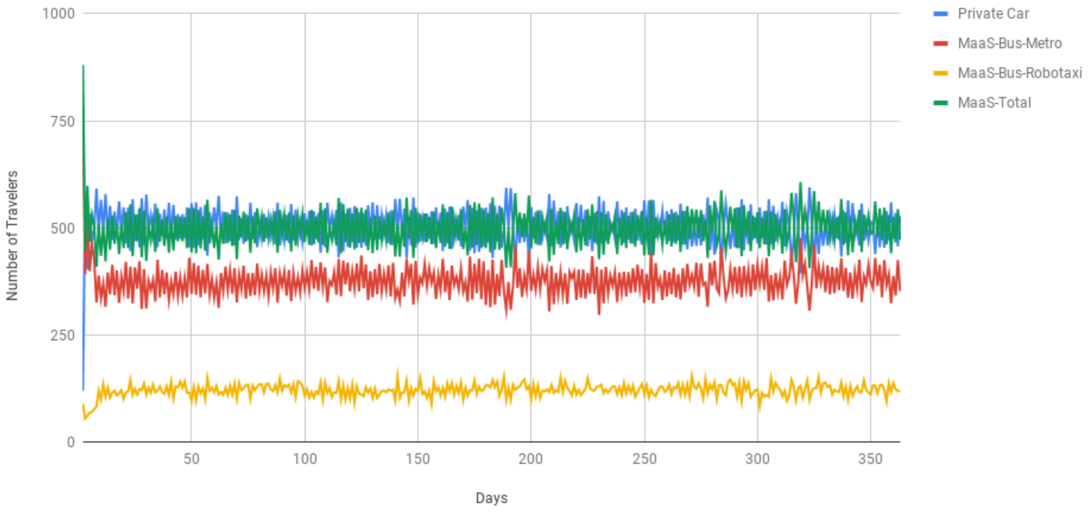


Figure 4.2: Variation of the number of *travelers* per transport mode

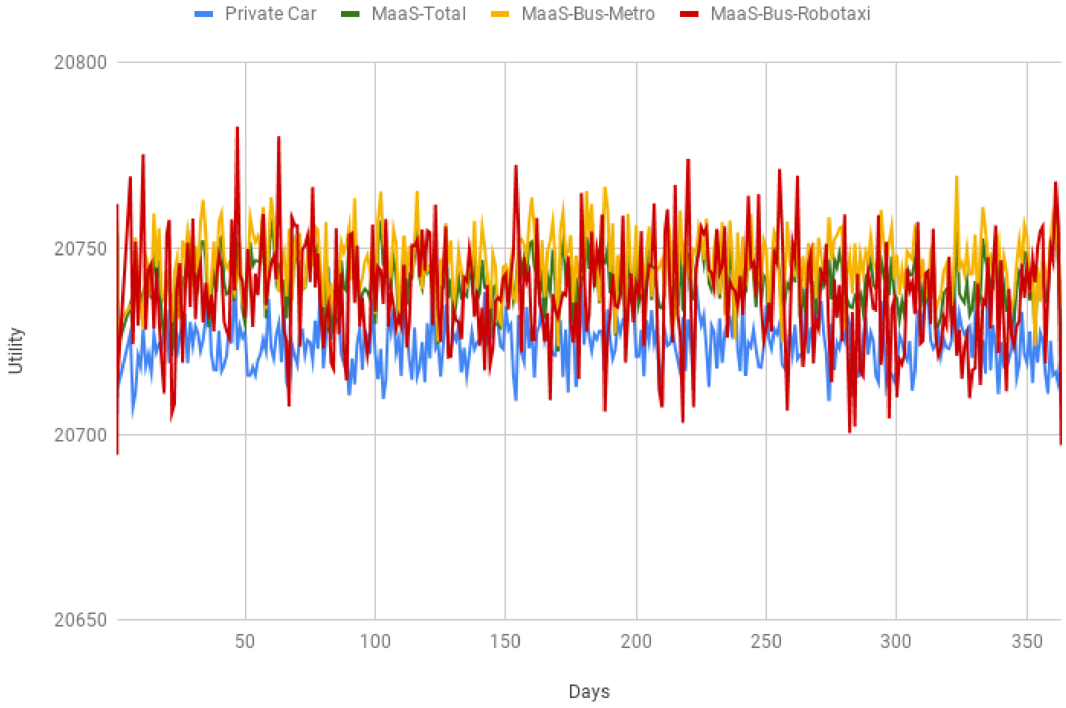


Figure 4.3: Variation of the utility of the *travelers* per transport mode

Regarding more specifically the services provided by the *MaaS Operator*, the option *bus+metro* is the most chosen, which is explained by the high value of propensity as shown in Figure 4.4. One possible cause could be related to the values of the parameters used for calculation of the utility, particularly the cost of usage associated with the option *bus+robotaxi*.

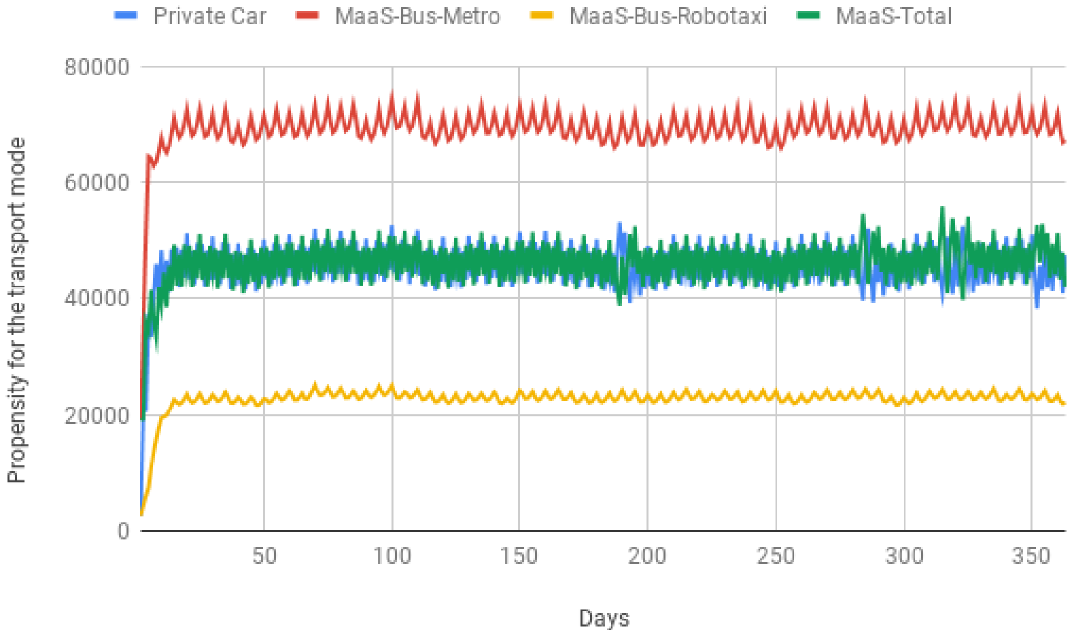


Figure 4.4: Variation of the propensities of the *travelers* per transport mode

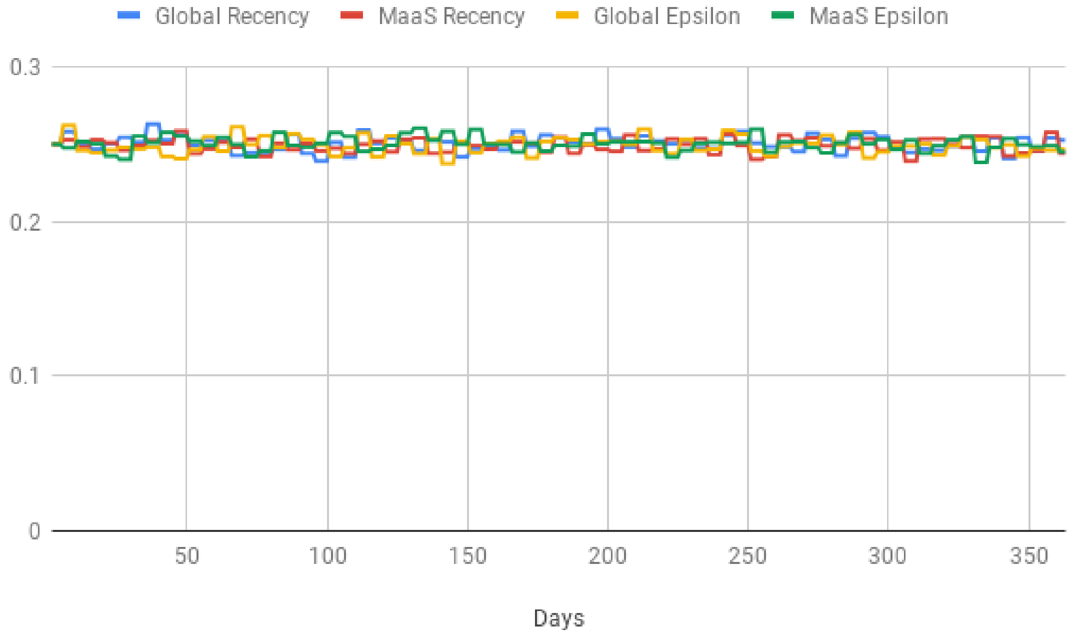


Figure 4.5: Variation of the *recency* and *epsilon* paramenters of Roth's and Erev's algorithm of the *travelers* per transport mode

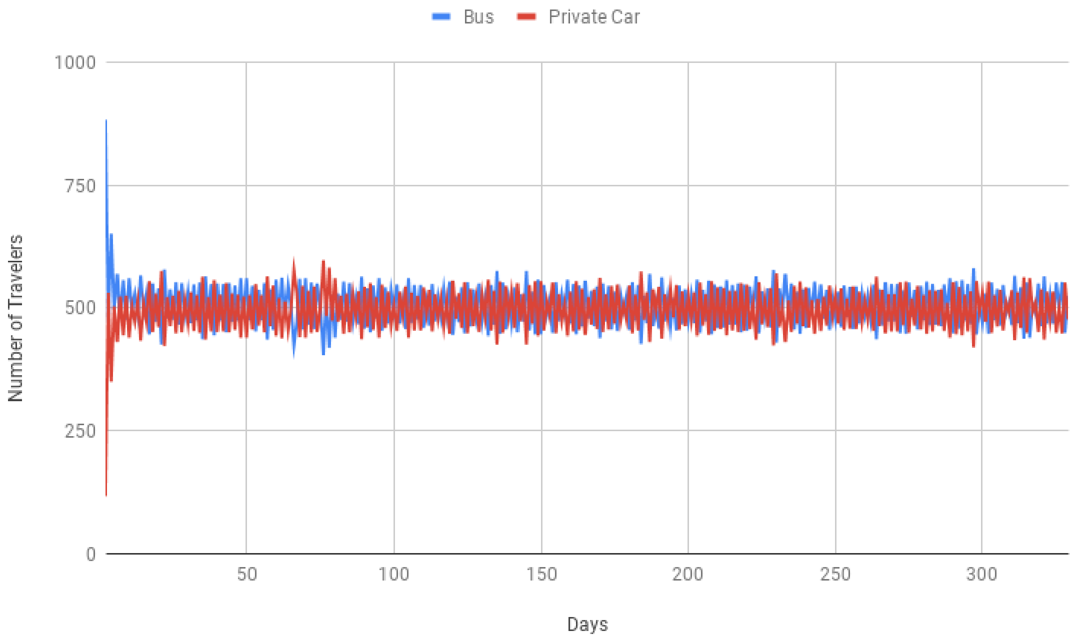


Figure 4.6: Variation of the number of *travelers* per transport mode

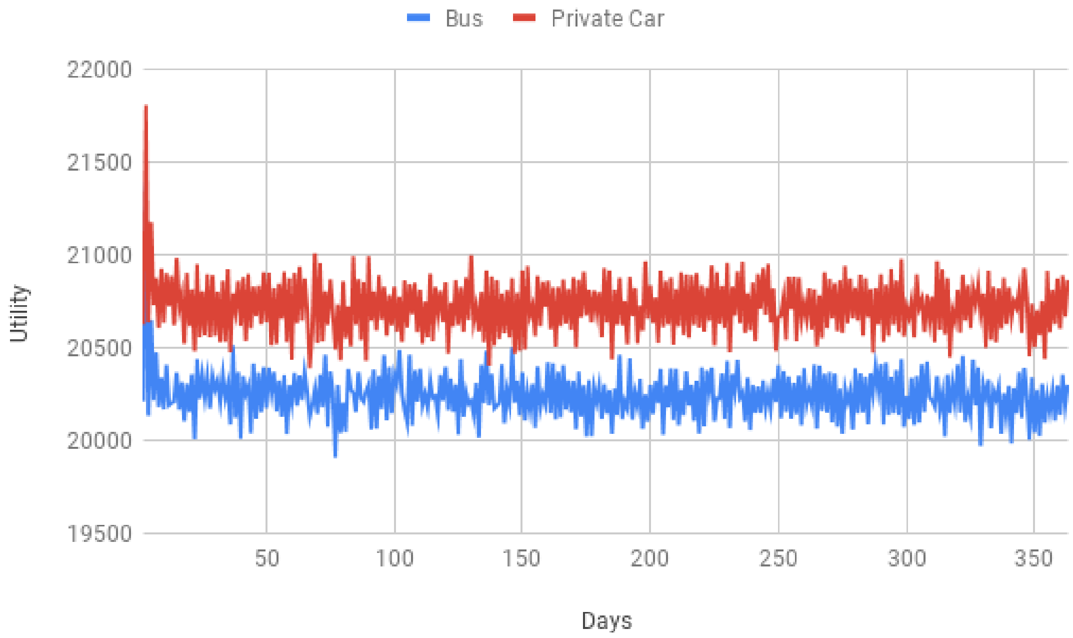


Figure 4.7: Variation of the utility of the *travelers* per transport mode

When comparing the simulation with private car and MaaS, and private car and bus, we can conclude from both simulations that, for the utility functions and parameter values used, the number of *travelers* that choose the private car option or the alternative option for that particular simulation is very similar as we can see in Figure 4.6. However, the utility of using bus compared to using private car is lower. This can be explained by the higher waiting time for the travelers that choose bus as transport mode. These variable has less impact when the *traveler* choose to use a public transport option through MaaS, as the he/she will be able to predict in a better way the fastest itinerary to choose, as well as reduce as much as possible the waiting time using the information provided by the *MaaS Operator*. Moreover, one of the options of the *MaaS Operator* provides metro as a transport mode which has significantly less waiting time and transport delays, as a result of the effect of traffic congestion being reduced as compared to bus.

With the application of a policy where we increased the usage of private car from 0.11 €/km to 1 €/km we could not see a significant variation of the number of *travelers* using private car, as well as the associated propensity to choosing private car remained similar to the one of MaaS, as we can see in Figure 4.8 and Figure 4.9. However, from analyzing Figure 4.10 we can observe that the utility decreased to the *travelers* that choose the private car, as expected from the application of the policy.

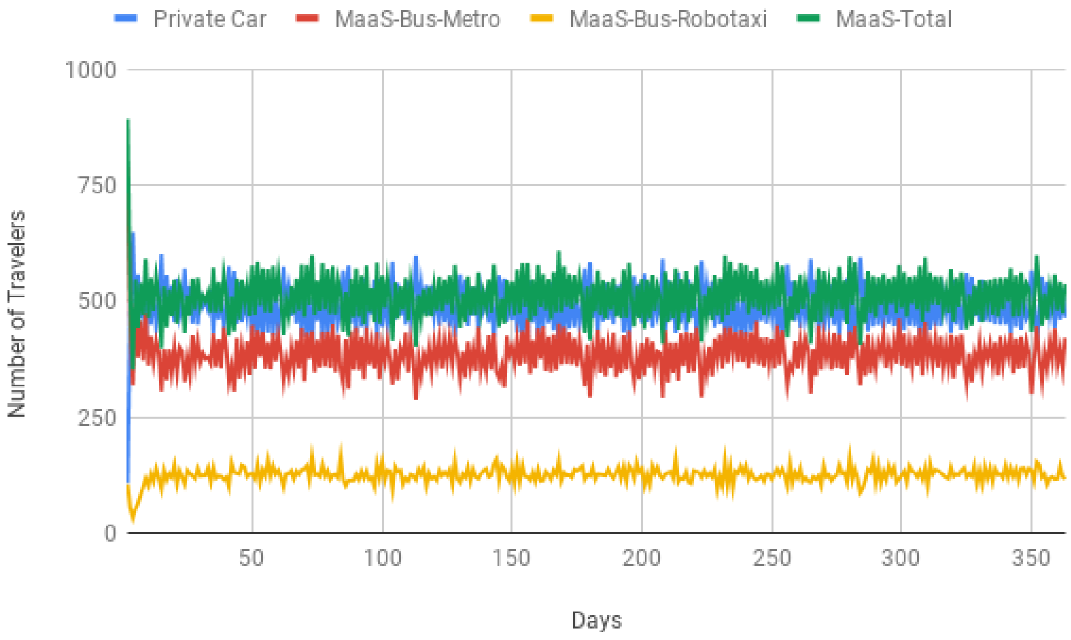


Figure 4.8: Variation of the number of *travelers* per transport mode (with policy of increased private cost applied)

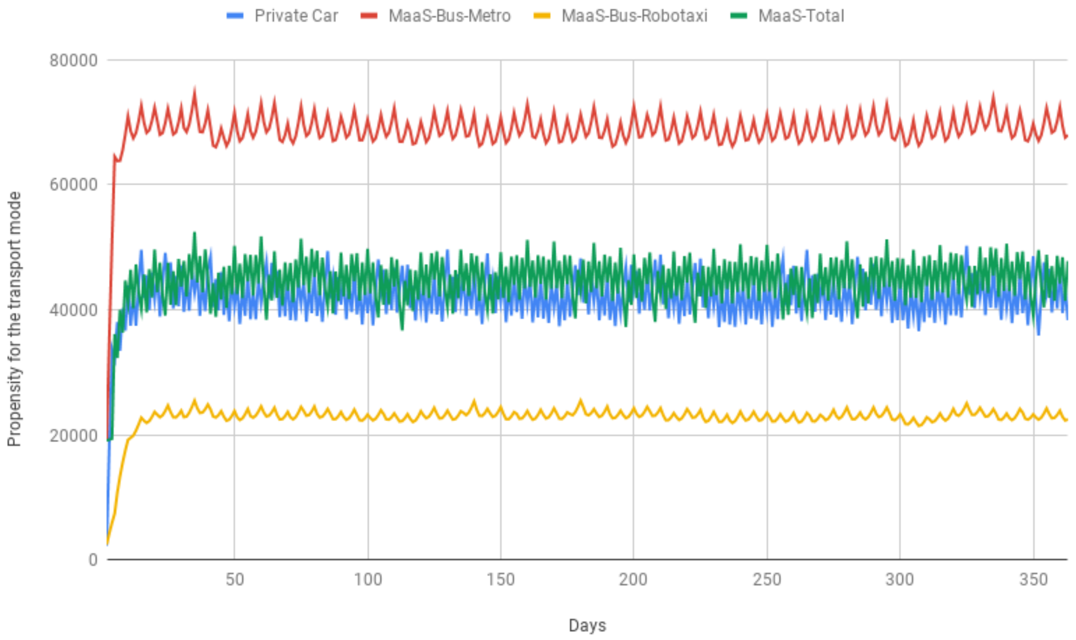


Figure 4.9: Variation of the propensities of the *travelers* per transport mode (with policy of increased private cost applied)

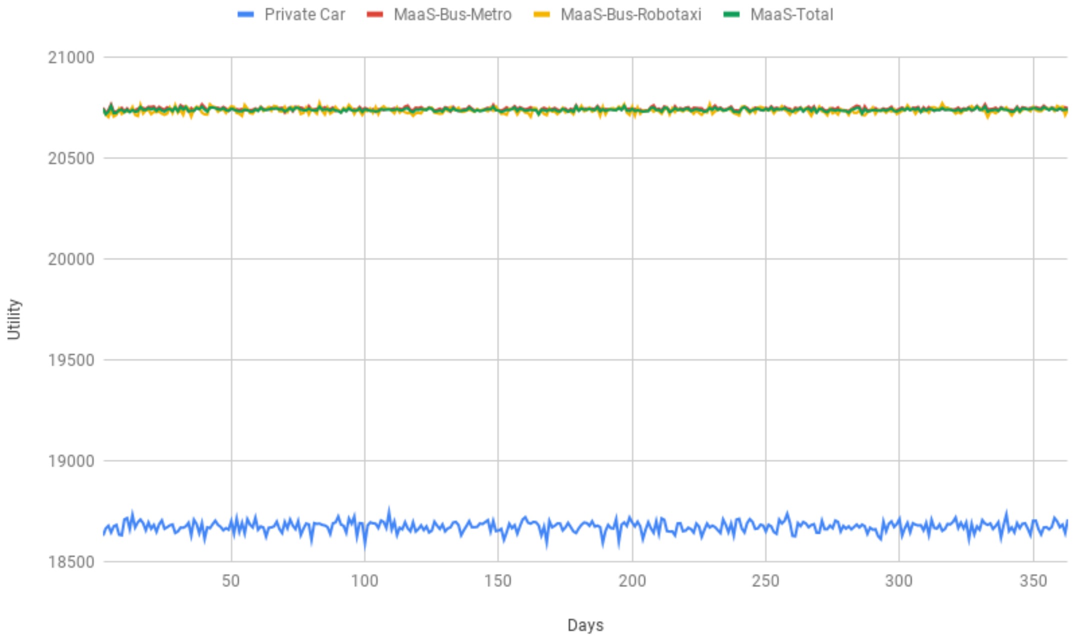


Figure 4.10: Variation of the utility of the *travelers* per transport mode (with policy of increased private cost applied)

4.3 Chapter Summary

In this chapter we presented the experimental design for the proof-of-concept for the proposed meta-model and associated methodology in Chapter 3. We have made 3 different experiments, using different combinations of transport modes, as well as one using a different policy. We were able to see that the demand of the system was capable using the proposed decision-making process to choose the transportation mode and ando also to *self-adapt* to changes in the environment.

Chapter 5

Conclusions

In this chapter we review the main concepts of the literature review, while also addressing the methodology and main conclusion of the experimental results. Lastly, we also give some perspective of the expected main contributions of the development of this work and also guide the way of future iterations.

5.1 Main Conclusions

In this work we started by reviewing several concepts regarding MaaS, AS and DM. MaaS is a relatively new concept that appeared as a possible solution for the current problems in mobility, particularly in the large urban areas. Heavy traffic condition, congestion, and long commute times, are a consequence of the increase in population, continuation of universal car ownership, but also a lack for the authorities of a model of MaaS that they can follow to address the particular issues of specific city. Next, through a gap analysis in presented in section 2.4 of bibliography review, we were able to identify a gap in in the current work trends regarding the the thematic in this work. As such, as main contributions of this work, we have proposed a methodology that combines analysis and design with the interactions between the agents of the system, in order to better represent an Artificial Society of *travelers* and how they interact with the other stakeholders present in the ecosystem of MaaS. We have also proposed a methodology for the automated generation and growing, through evolution, of an Artificial Society inspired in the concepts of Reinforcement Learning and Clonal Plasticity. Finally, we also developed model of simulation for MaaS where we instantiated the proposed meta-model in this work, as a proof-of-concept. After some experiments, we were able to see how the Artificial Society was *self-adapting* to the inputs received of the environment and how it was influencing the decision-making of each *traveler*.

5.2 Limitations

During the execution of this work we had some limitations, starting by the fact we were not able to evaluate to automated generation of populations as we have proposed in our methodology. This was due to the fact that we were not able to dedicate a phase to data generation through censuring or inquiries. Moreover, the developed simulation model works as a proof-of-concept of the proposed methodology, with a bigger focus in the evolution and *self-adaptation* of the demand in response to changes in the system. Furthermore, the developed simulation model is intended to be a starting point for more complex models with the aim to create a decision tool to help in the implementation of policies regarding the transport system,

5.3 Future Work

As future work, we consider that would be interesting see how the *MaaS Operator* could create in real-time trips or mobility packages according to the trip requirements of the *travelers* and how it would influentiate their decision-making. Moreover, still related to the *MaaS Operator* we would to see how a *traveler* choosing to subscribe a mobility package instead of buying a trip as pay-as-go could have influence in the next time the *traveler* would need to travel. Finally, in this work we have focused in the demand modelling and how the demand evolves to the changes of the supply and the environment. It could be interesting to also evaluate the supply modelling and how it evolves to the changes of the cycle. Therefore, we would be able to model a full cycle of equilibrium between demand and supply.

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