Deliverable 2.3

Definition of new concepts, variables, and KPIs

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007153.

Project acronym	**nuMIDAS**
Project title	New Mobility Data and Solutions Toolkit
Project number	Horizon 2020 MG-4-8 – GA No 101007153
Work package	WP2 – Status and trend assessment
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Reviewer(s)	CTU
Dissemination level	Public
Contractual delivery date	28/02/2022 (M14)
Actual delivery date	09/12/2022 (M24)
Version	V1.0

Document revision history			
Version	**Date**	**Description**	**Editor(s) (Affiliation Short Name)**
v0.1	13/01/2022	Structure and first draft	M. Hyksova (CTU)
v0.2	09/02/2022	Updated variables and key performance indicators	M. Hyksova (CTU)
v0.3	27/02/2022	Updated requirements on data First submitted version	S. Maerivoet (TML)
v0.4	20/07/2022	Updated variables and key performance indicators for the nuMIDAS toolkit and requirements on data	M. Hyksova (CTU)
v0.5	07/12/2022	Updated variables and key performance indicators for the nuMIDAS toolkit and requirements on data with the last version of the use cases. Updated conclusions and executive summary Second submitted version	A.M. Pereira (CTU)
V1.0	09/12/2022	Final review for submission	S. Maerivoet (TML)

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Acronyms and abbreviations

CAV	Connected and Automated Vehicle
C-ITS	Cooperative ITS (Intelligent Transport Systems)
CO2 / CO_2	Carbon dioxide
CPS	Cyber-Physical System
EC	European Commission
EU	European Union
EV	Electric Vehicle
FCD	Floating-Car Data
GA	Grant Agreement
GIS	Geographic Information System
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICCT	International Council on Clean Transportation
ICT	Information and Communication Technologies
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
MAS	Multi-agent system
nuMIDAS	New Mobility Data and Solutions Toolkit
OD	Origin-Destination
PMV	Personal Mobility Vehicles
PT	Public Transport
PTM	Public Transport Management
SoA	State of the Art
TDM	Travel Demand Management
VKT / VMT	Vehicle Kilometres Travelled / Vehicle Miles Travelled
V2V / V2I	Information exchange between vehicles / between vehicles and roadside infrastructures
WP	Work Package

1 Executive summary

The mobility ecosystem, seen in Figure 1, can be viewed as a complex system, which is a subsystem of a city, another complex system in the sense of systems theory. A system comprising many units where the interaction between the units results in an emergent behaviour is known as a complex system (Smith et al, 2003). Here, emergent behaviour is a behaviour of the system that is not characteristic of the individual units of the system, but the result of the interaction between the systems.

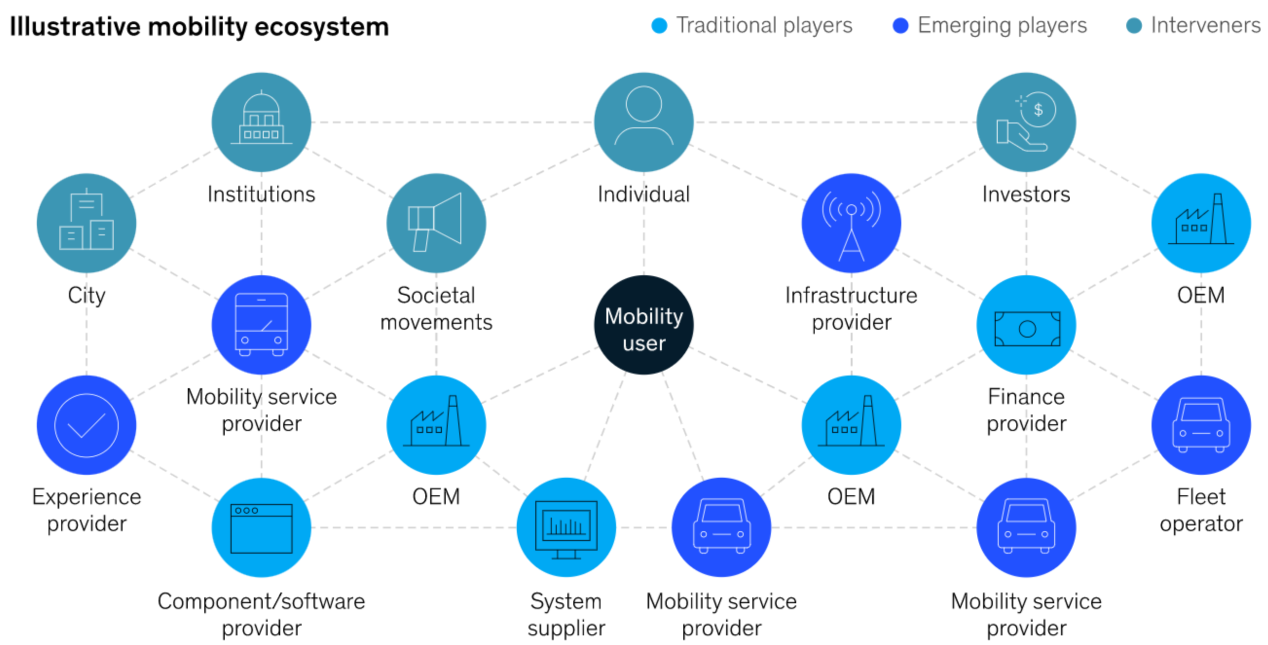


Figure 1: Mobility service-centric ecosystem[1]

A useful tool used for modelling and simulation of complex systems of a distributed nature represent multi-agent systems. Rzevski and Skobelev (2014) denoted multi-agent technology as the key software technology for managing complexity. Multi-agent systems (MAS) are composed of several autonomous entities, known as intelligent agents. An agent can stand not only for a software agent or a robot, but also for a model of a human or some institution or any other entity. MAS can therefore be used also for the simulation of the actions of various participants in the mobility system. In these *agent-based models* (ABM), individual travellers and also individual vehicles are treated as autonomous agents with their own goals and behaviours that learn and update their travel patterns iteratively on the basis of defined rules, as they interact among themselves and with the environment (Scherr, 2020). By creating ABMs, simulations can be run with different constraints and configurations, allowing researchers to see the impact certain things have on the convergence or emergent behaviours of a scenario. Agents and multi-agent systems have been applied over the years as an enabling concept underlying the transformation of traditional transportation systems, especially into more cooperative intelligent transportation systems (C-ITS) and new mobility paradigms.

[1] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/defining-and-seizing-the-mobility-ecosystem-opportunity

A standard tool for the analysis of agents' interactions and behaviour represents game theory. In general, the concept of *a game* denotes any decision situation, the result of which depends on decisions of at least two different entities, so-called players, which have at least two different strategies to choose from. These players can be, e.g., various firms in the market, politicians, political parties, shareholders, travellers, users of various networks, participants of a military conflict, creditors of a bankrupted company, or even genes that control the behaviour of their bearers in certain situations. There exist various branches of game theory, one possible classification is depicted in Figure 2.

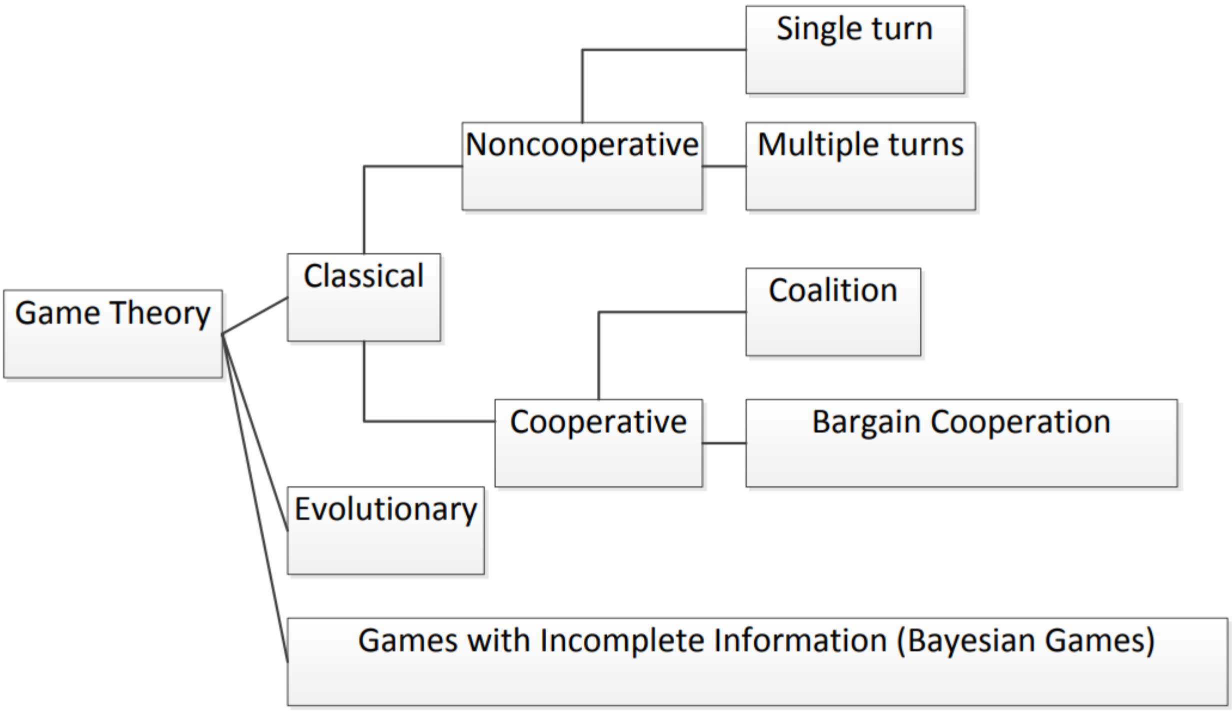


Figure 2: Classification of games[2]

In Deliverable 2.1, stakeholders involved in different mobility services are discussed together with the corresponding business models. As seen in Figure 3, we can observe different groups of actors (firms, government, customers) whose interests are often competing (costs, benefits), but they also have shared goals and contribute to the value co-creation. Different actors interact with each other, have different strategies to choose from, their "payoffs" depend not only on their own action, but also on the action of other actors, and these interactions should be taken into account in decision processes. The system can therefore be modelled as a game in the sense of game theory.

[2] https://arxiv.org/vc/arxiv/papers/1704/1704.00323v1.pdf

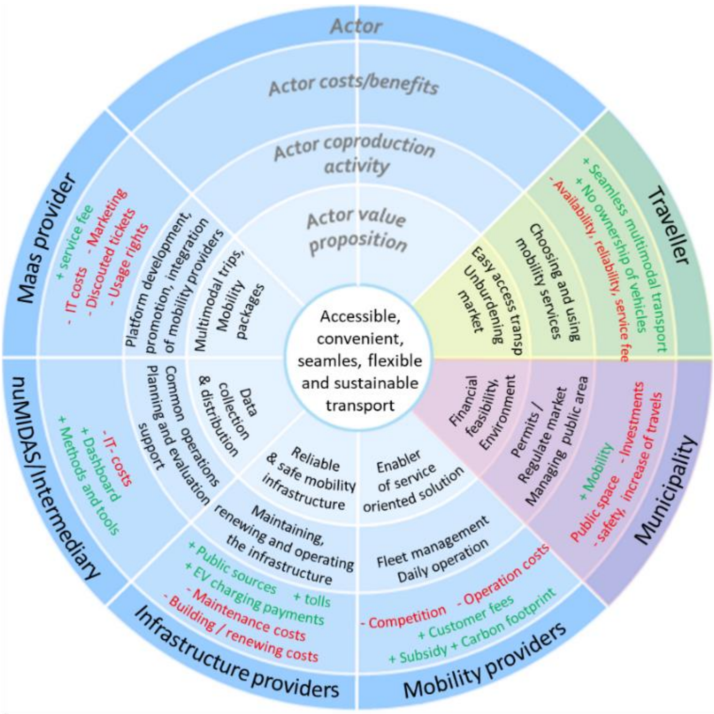


Figure 3: Business model radar for Mobility-as-a-service

The nuMIDAS toolkit is intended as a decision support tool for policy makers at a municipality level, helping them to foresee impacts of various policies and make the decision that is beneficial for the society and acceptable by all sides. All selected use cases can be viewed as instances of a Stackelberg game with the municipality as a single leader and travellers or also mobility service providers as followers. Strategies selected by followers then determine the payoff of the leader, who has to include the best responses of followers to various strategies before the selection of the action. For instance, the performance of a decision on parking has implications for economy, location and intensity of various activities, environment, the quality of life and social cohesion. To obtain a more detailed picture of the impacts of various scenarios, the nuMIDAS toolkit user will also be provided a full table of Key Performance Indicators (KPIs), **Error! Reference source n ot found.** provides an example of such game on the decision on a parking policy.

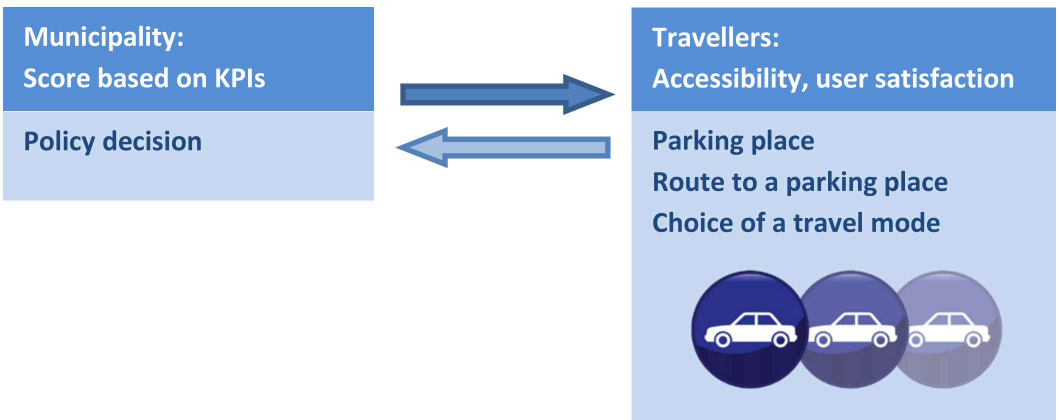


Figure 4: Decisions on parking policies as a Stackelberg game

These KPIs were selected in compliance with the recommendations of Organisation for Economic Co-operation and Development (OECD) and United Nations for Smart Sustainable Cities. Additionally, they are also planned according to the capabilities of each tool and tailormade according to the needs of the municipalities. They were proposed with the aim to provide a holistic view by capturing three dimensions, namely environmental, economic, and social, and allow a municipality as a user of the nuMIDAS toolkit to reach a balance among them, as seen on Figure 5.

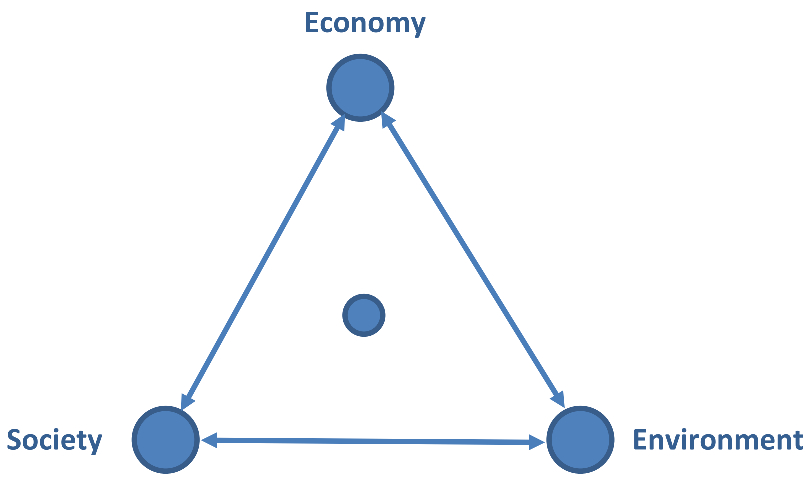


Figure 5: Balance of social, economic, and environmental aspects (adapted from (Flint, 2013))

Last but not least, we also provide lists of the input data requirements for individual use cases to ensure clarity over the necessary inputs of each tool, specifying units and briefly describing how each input should look like.

2 Introduction

2.1 About nuMIDAS

The mobility ecosystem is rapidly evolving, whereby we see the rise of new stakeholders and services. Examples of these are the presence of connected and automated vehicles, a large group of organisations that rally to establish various forms of shared mobility, with the pinnacle being all of these incorporated into a large MaaS ecosystem. As these new forms of mobility offerings start to appear within cities and regions[3], so do new ways in which data are being generated, collected, and stored arise. Analysing this (Big) data with suitable (artificial intelligence) techniques becomes more paramount, as it leads to insights into the performance of certain mobility solutions, and it can highlight (mobility) needs of citizens in a broader context, and in addition to a rise in new risks and various socio-economic impacts.

Successfully integrating all these disruptive technologies and solutions within the designs of policy makers remains a challenge at current, let alone being able to analyse, monitor, and assess mobility solutions and their potential socio-economic impacts.

nuMIDAS (new mobility data & solutions toolkit), bridges this (knowledge) gap, by providing insights into what methodological tools, datasets, and models are required, and how existing ones need to be adapted or augmented with new data. To this end, it starts from insights obtained through (market) research and stakeholders, as well as from quantitative modelling. A wider applicability of the project's results across the whole EU is guaranteed as all the research is validated within a selection of case studies in pilot cities which have varying characteristics. This gives thereby credibility to these results. Finally, through an iterative approach, nuMIDAS creates a tangible and readily available toolkit that can be deployed elsewhere, including a set of transferability guidelines, thus thereby contributing to the further adoption and exploitation of the project's results.

nuMIDAS, the New Mobility Data and Solutions Toolkit, started at the beginning of 2021 under the Horizon 2020 programme and it is being developed by a European Consortium, composed of 9 partners from 6 countries: Belgium, Czech Republic, Greece, Italy, The Netherlands, and Spain.

The project builds on a distributed selection of case studies in pilot cities to provide geographic coverage of the EU. The four pilot cities are: Barcelona (Spain), Milan (Italy), Leuven (Belgium), and Thessaloniki (Greece).

[3] When talking about a 'smart concept', the term 'smart cities' is typically used. We need to keep in mind that it covers not only cities, but also regions as they are binding the cities, smaller and larger, together to realise the necessary installed base, coordinate together the approach and especially keep the borders fuzzy.

2.2 Purpose of this document

This deliverable summarises the findings of Task 2.4 and provides an overview of new concepts, new variables, requirements on data, and KPIs that allow for the quantification of the suitability and usability of new research methods and tools developed and analysed in Task 3.2. The cited Task 2.4 built upon the previous tasks in WP2, namely upon the state-of-the-art analysis of available methods and tools for various mobility services, and stakeholder and business model analysis summarised in Deliverable 2.1, and on the analysis of selected use cases provided in Deliverable 2.2.

2.3 Structure of this document

The structure of this document is determined by the perception of the mobility ecosystem as a complex system, and how the interactions between different players can be viewed from the game theoretical perspective for policy making. Chapter 3 starts with a brief outline of the concepts related to complex and multi-agent systems, then it introduces the basic concepts of game theory and discusses its relation to the domain of transportation and policy making.

As the focus of this document lies also on variables and KPIs, Chapter 4 is dedicated to variables and key performance indicators proposed for the nuMIDAS toolkit intended as a decision support tool for policy makers at a municipality level, helping them to foresee impacts of various policies and make the decision that is beneficial for the society and acceptable by all sides. This chapter begins with a general description of environmental, economic, and social indicators, then the indicators for individual use cases are introduced together with the method of computation of the resulting score. Chapter 5 provides a summary of expected requirements on data for nuMIDAS use cases. Finally, Chapter 6 provides conclusions on how this document provides aggregated value on assessments of alternative scenarios given simple KPIs that measure trade-offs between different players of the mobility ecosystem and different objectives of the decision maker.

3 Conceptual and methodological framework

3.1 Complex systems

3.1.1 Mobility ecosystem as a complex system

Using the terms of systems theory, mobility ecosystem can be viewed as a complex system. Here we understand the concept of a system in the sense of the definition formulated by Rousseau (2015), i.e., as a set of interacting or interdependent component parts forming a complex whole. Every system is delineated by its spatial and temporal boundaries, surrounded, and influenced by its environment, described by its structure and purpose, and expressed in its functioning.

A system comprising a large number of units where the interaction between the units results in an emergent behaviour is known as a complex system (Smith et al, 2003). Here, emergent behaviour is a behaviour of the system that is not characteristic of the individual units of the system, but the result of the interaction between the systems. A good example of a complex system is a human brain, where a collection of neurons connected to each other results in emergent properties such as memory, emotion, intelligence etc. Similarly, a turbulent flame can be considered as a collection of flamelets interacting with each other and the other subsystems that constitute a combustion system (Sujith & Unni, 2020).

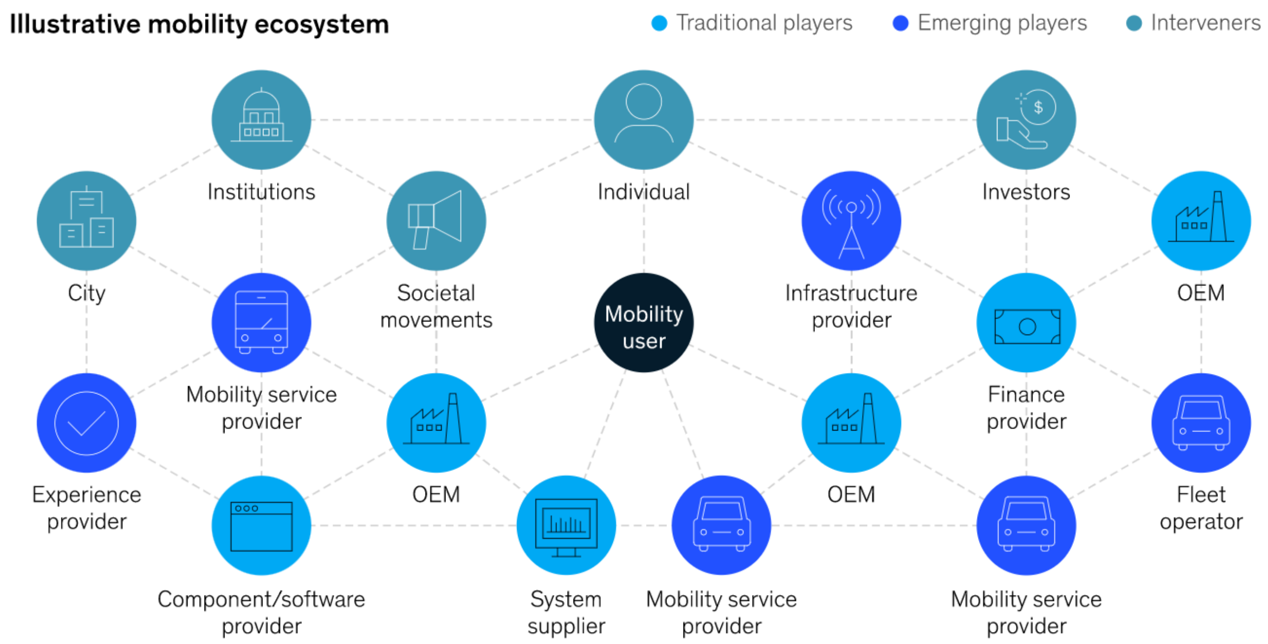


Figure 6: Mobility service-centric ecosystem[4]

[4] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/defining-and-seizing-the-mobility-ecosystem-opportunity

3.1.2 Mobility ecosystem as a subsystem of a (smart) city

Mobility ecosystem can be viewed as a subsystem of a city, another complex system. It is interrelated with other systems including energy and urban systems, and its performance has implications for economy, location and intensity of various activities, environment, the quality of life and social cohesion. Improved mobility may lead to the change of a location of people and industry, and similarly a change in land use, such as building of new houses, factories, business centres etc., has an influence on travel demand (Cascetta et al., 2007). On the other hand, the interconnection of different systems and subsystems among themselves to increase the quality of life, energy savings or to reduce emissions, is one of the main goals of smart cities.

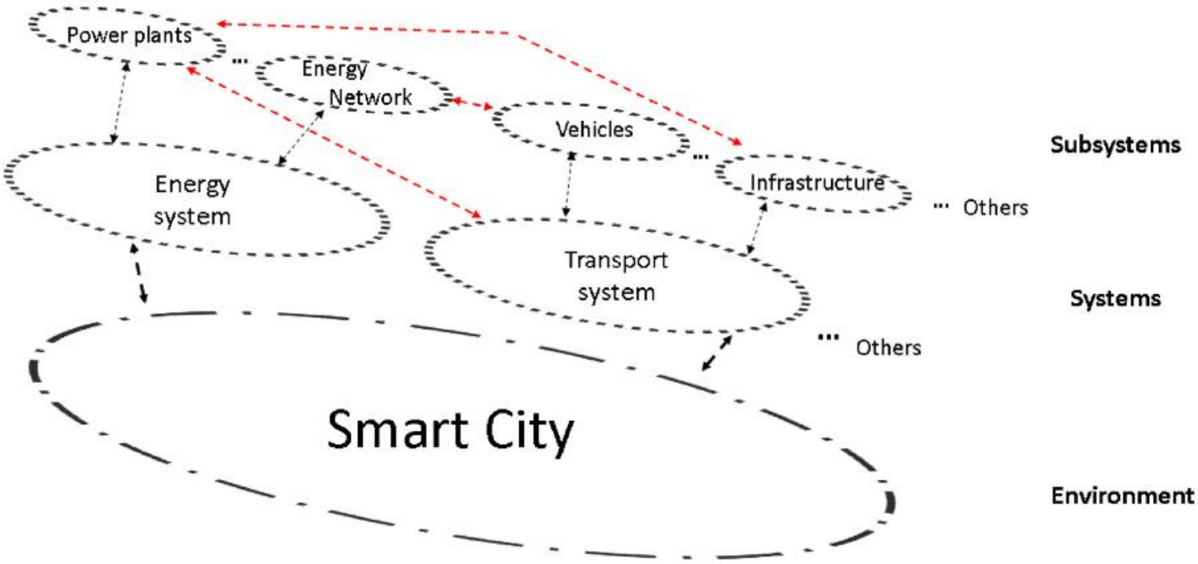


Figure 7: The example of a smart city fitted to the Systems Theory (Lom & Pribyl, 2021)

For example, in a smart city an electric car is able to communicate directly with the energy network and reserve a necessary capacity and a charger, or the infrastructure can communicate directly with power plants to optimise energy supplies based on the demand from vehicles at the infrastructure (Lom & Pribyl, 2021).

The smart city can be classified as a Cyber-Physical System (CPS), which denotes transformative technologies for managing interconnected systems between its physical assets and computational capabilities (Lee et al., 2015). In a CPS, computing elements coordinate and communicate with sensors, which monitor physical indicators, and actuators, which modify the physical environment where they operate. CPS often seeks to control the environment in some way. CPS uses sensors to connect all distributed intelligence in the environment to gain a deeper knowledge of the environment which enables a more accurate control. In a physical context, actuators act and modify the environment where users live. In a virtual context, CPS is used to collect data from the virtual activities of users such as their involvement in social networks or e-commerce sites. Then, CPS responses to this data to predict actions or needs of users as a whole (Lom & Pribyl, 2021).

3.2 Multi-agent systems as a tool for dealing with complexity

3.2.1 Multi-agent systems

A useful tool used for modelling and simulation of complex systems of a distributed nature represent multi-agent systems. Rzevski and Skobelev (2014) denoted multi-agent technology as the key software technology for managing complexity.

Multi-agent systems (MAS) are composed of several autonomous entities, known as intelligent agents. These agents do not have to be homogeneous — they could be software agents, robots or even humans. Each agent acts within a shared environment, and has its own set of goals and constraints. MAS research investigates the control and modelling of complex systems made up of these interacting agents.

3.2.2 Multi-agent systems in transportation

Technologies based on MAS technologies are used to model, simulate, optimise, and manage large-scale, heterogeneous, multimodal, and complex transportation systems. The applications include[5]:

- Applications in traffic, transportation, and transport logistics
- Optimisation (e.g., traffic assignment, routing, route choice)
- Coordination in intelligent transportation systems
- Intelligent, adaptive traffic control[6]
- Distributed decision making in traffic, transportation, and transport logistics
- Multi-agent systems for intelligent vehicles
- Mobile devices in smart transportation systems
- Autonomous vehicles and collaborative driving
- Self-* properties of traffic systems
- Agent-based approaches to modelling driver behaviour
- Agent-based simulation of traffic and transportation systems
- Agent-based pedestrian and crowd simulation
- Shared and on-demand mobility (car sharing, ride sharing, Mobility as a Service, etc.)

C-ITS: Cooperative Intelligent Transportation Systems

Future transportation systems are expected to follow a cooperative approach where vehicles become one of the numerous providers of a very complex multi-agent system (Rufino et al., 2019). This implies an increasing importance of Cooperative Intelligent Transportation Systems (C-ITS), a subclass of Intelligent Transportation Systems (ITS) that exploit short- and long-range communications to digitally connect and enable information exchange between vehicles (V2V), vehicles and roadside infrastructures (V2I), as well as vehicles and other road users, such as pedestrians, cyclists, and motorcyclists (Edwards & Zunder, 2018; Pribyl et al., 2021).

[5] https://www.gdria.fr/bull-ia-multi-agent-systems-in-transportation-systems-amsta-19-st-julians-malta-17-19-june-2019

[6] https://www.sciencedirect.com/science/article/pii/S0378437121006294

As discussed in (Guériau et al, 2015), C-ITS are complex systems well-suited to a multi-agent modelling that ensures a smooth cooperation between non cooperative and cooperative vehicles, that communicate with each other (V2V communication) and the infrastructure (I2V and V2I communication).

Ahmed, E. and Gharavi, H. (2018) provide a survey of results in the domain of cooperative vehicular networking. As they mention: Saad et al. (2011) propose a cooperative protocol for RSUs in vehicular networks to optimise revenues generated from data dissemination. The problem of revenue optimisation is formulated as a coalition game among RSUs. In a coalition game, multiple players form a group to participate in a game instead of participating individually. Then, a distributed algorithm for coalition formation is proposed that enables RSUs to distributively join and leave a coalition while optimizing their utility. The utility considers the gain from cooperation and cost incurred on coordination. Simulation results demonstrate that the proposed algorithm enables RSUs to self-organise while enhancing the payoff between 20.5 % and 33.2 % as compared to the non-cooperative case.

3.2.3 Agent-based models

An agent can stand not only for a software agent or a robot, but also for a model of a human or some institution or any other entity. MAS can therefore be used also for the simulation of the actions of various participants in the mobility system. In these *agent-based models* (ABM), individual travellers and also individual vehicles are treated as autonomous agents with their own goals and behaviours that learn and update their travel patterns iteratively on the basis of defined rules, as they interact among themselves and with the environment (Scherr, 2020).

By running a simulation of an ABM, complex emergent behaviours can be observed on a system level, despite agents only taking relatively simple actions. By creating ABMs, simulations can be run with different constraints and configurations, allowing researchers to see the impact certain things have on the convergence or emergent behaviours of a scenario. Recent applications of ABMs include smart grid and electric vehicle research, and public health (e.g. epidemiology research)[7].

Agents and multi-agent systems have been applied over the years as an enabling concept underlying the transformation of traditional transportation systems, especially into more cooperative intelligent transportation systems (C-ITS) and new mobility paradigms.

[7] https://medium.com/swlh/whats-hot-in-multi-agent-systems-4b0f348e68bd

3.3 Game theory as a common framework

A standard tool for the analysis of agents' interactions and behaviour represents game theory. In general, the concept of *a game* denotes any decision situation, the result of which depends on decisions of at least two different entities, so-called players, which have at least two different strategies to choose from.

These players can be, e.g., various firms in the market, politicians, political parties, shareholders, travellers, users of various networks, participants of a military conflict, creditors of a bankrupted company, or even genes that control the behaviour of their bearers in certain situations. The domain of applications of game theory is therefore very wide, as it is depicted in Figure 8.

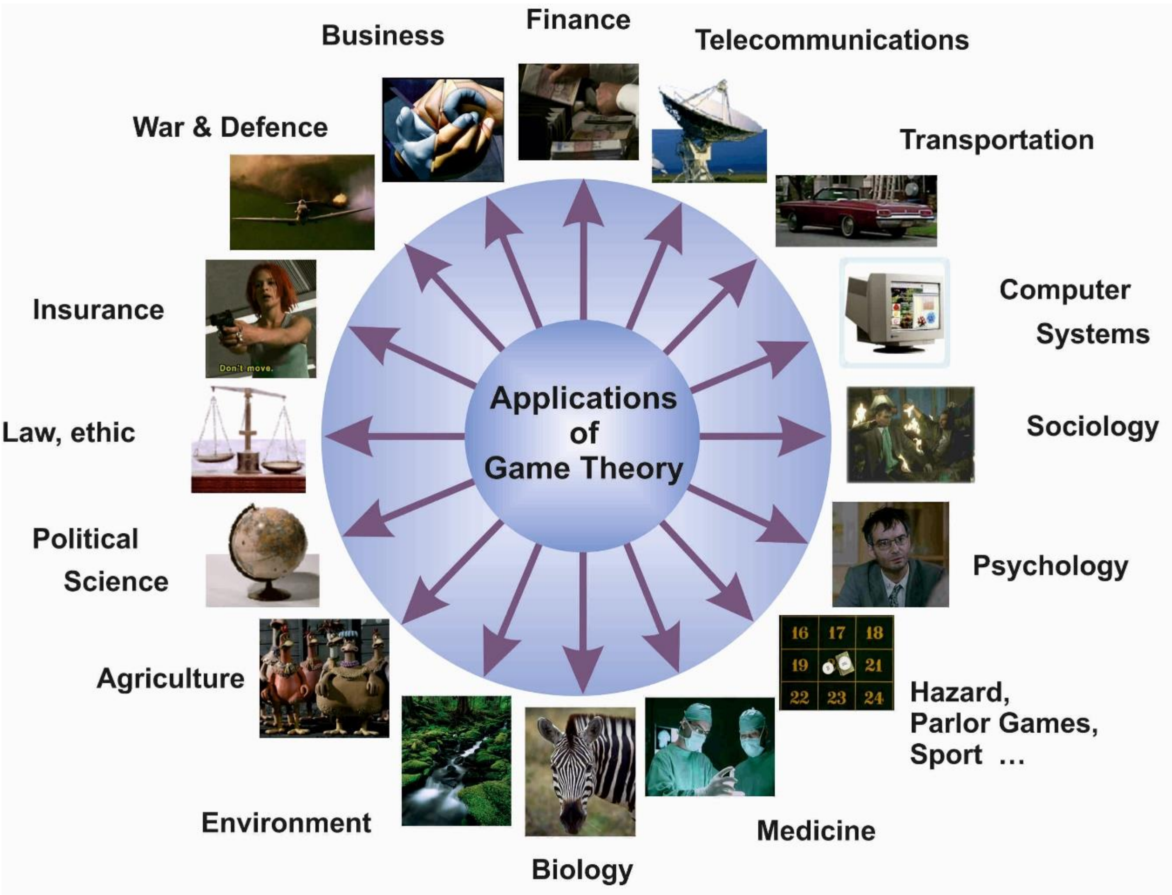


Figure 8: Application domains of game theory

For the definition of a solution concept and practical use of game theory, it is necessary to characterise a game in a narrower way. Obviously, models are different for different level of cooperation or communication of players, for different organisation of a "game" (e.g., simultaneous or sequential decision making, one-time or repeated game), different level of available information or rationality etc. There exist various branches of game theory; one possible classification is depicted in Figure 9.

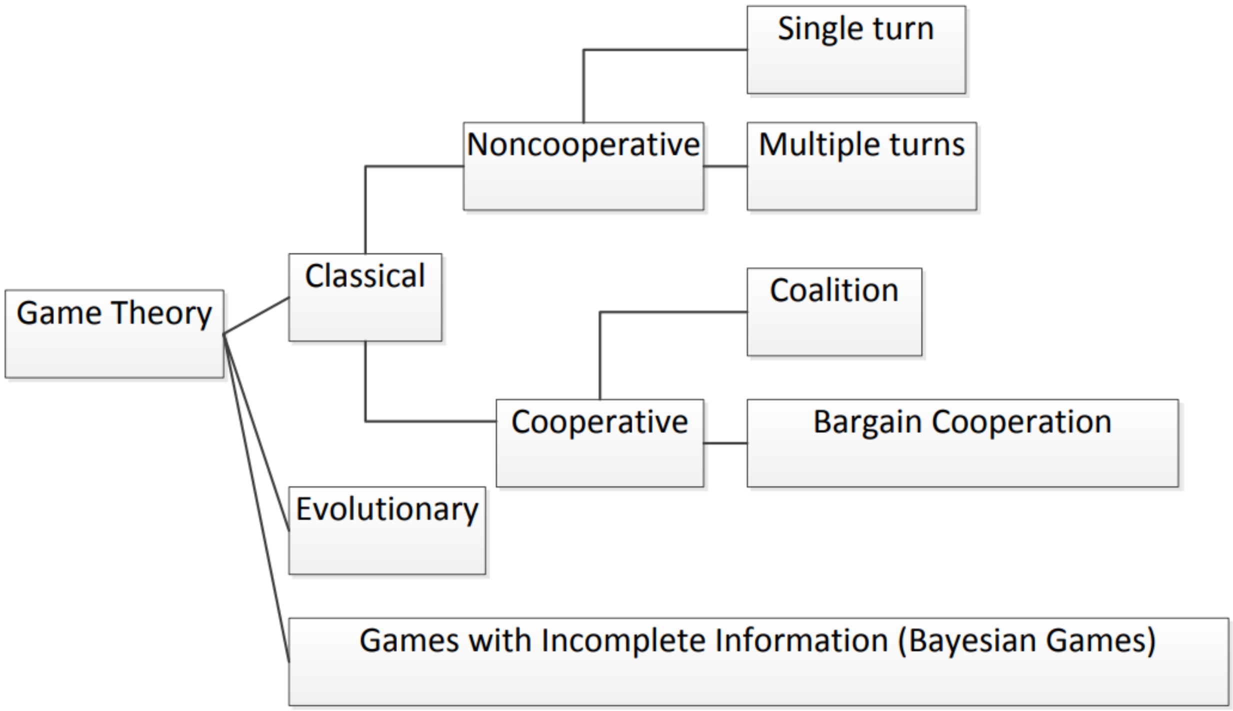


Figure 9: Classification of games[8]

3.3.1 Mobility ecosystem as a game

3.3.1.1 Business model radar as a representation of actors in a game

In Deliverable 2.1, stakeholders involved in different mobility services are discussed together with the corresponding business models. As seen in Figure 10, we can observe different groups of actors (firms, government, customers) whose interests are often competing (costs, benefits), but they also have shared goals and contribute to the value co-creation. Different actors interact with each other, have different strategies to choose from, their "payoffs" depend not only on their own action, but also on the action of other actors, and these interactions should be taken into account in decision processes. The system can therefore be modelled as a game in the sense of game theory.

Moreover, the improvement of a traffic system requires considering impacts of various decisions from different perspectives, i.e., from the point of view of travellers, society, service providers etc. In a game theoretical model, these considerations are included in the analysis of payoff functions of different players.

Game theory also provides a solid background for modelling and analysis of various types of interactions that can be one-time or repeated, proceed simultaneously or sequentially, there can be various extent of available information, rationality, and possible cooperation.

[8] https://arxiv.org/vc/arxiv/papers/1704/1704.00323v1.pdf

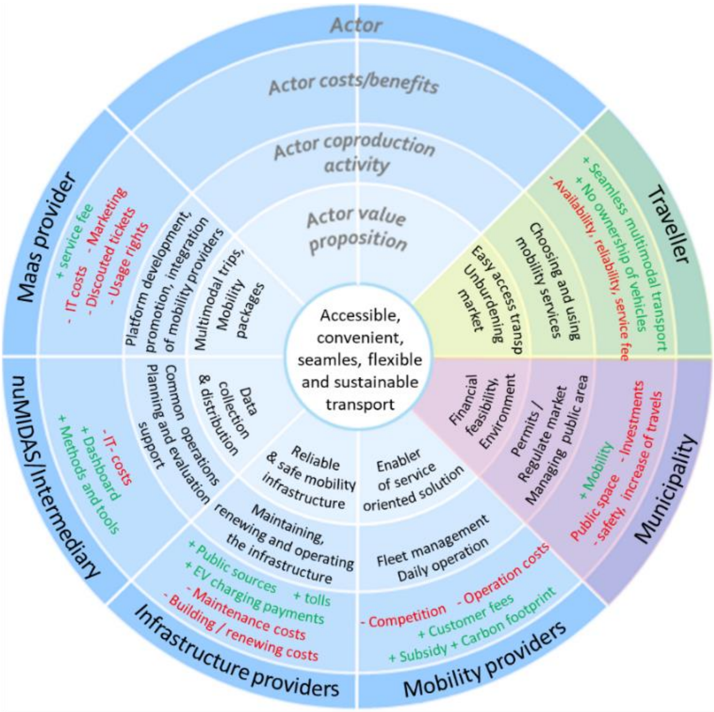


Figure 10: Business model radar for Mobility-as-a-service

3.3.1.2 Basic elements of game-theoretic representation

A game-theoretic model requires the specification of the following basic elements:

Players / actors / agents

E.g., transport service operators (taxi, PT, freight shipper, transportation network companies), infrastructure providers (station operators, airports, air traffic control providers, road and bridge network providers, railway infrastructure companies – may be public or private), regulators and government departments, travellers.

Strategies available to each actor

E.g., network choice, fleet types, timetables, frequencies, fares, tolls, and subsidies for transport operators, setting capacities, number of licenses, safety levels, investments; travel mode, route/

Payoff received by each actor per combination of strategies chosen by involved stakeholders (objective functions).

E.g., profit, subsidies, costs, travel time (or its monetary value), social welfare.

3.3.2 Policy making from game theoretical perspective

3.3.2.1 Single-leader multi-follower Stackelberg game

The nuMIDAS toolkit is intended as a decision support tool for policy makers at a municipality level, helping them to foresee impacts of various policies and make the decision that is beneficial for the society and acceptable by all sides.

All selected use cases can be viewed as instances of a Stackelberg game with the municipality as a single leader and travellers or also mobility service providers as followers. In this game, the leader moves first and makes a decision of a certain policy, as for example a parking policy, establishment of a low-emission zone, rules for shared mobility providers, policy related to taxes, public transport prices etc. The aim of the municipality is to maximise social welfare expressed as a score based on selected and/or aggregated key performance indicators discussed in Chapter 4. To obtain a more detailed picture of the impacts of various scenarios, the nuMIDAS toolkit user will also be provided a full table of KPIs.

As soon as the rules are given, a simultaneous game between the followers proceeds, in which each of them searches a best reply to the action of the leader and also to the action of other followers. Strategies selected by followers then determine the payoff of the leader, who has to include the best responses of followers to various strategies before the selection of the action.

Example: Decision on a parking policy

Leader: Municipality

Strategy to select: parking policy (parking restrictions, parking prices),

Payoff: score based on KPIs (to be maximised)

Followers: Car drivers searching parking place

Strategy to select: parking place and a route towards it, selection of another transport mode

Payoff: accessibility (economic, operational, and physical), user satisfaction

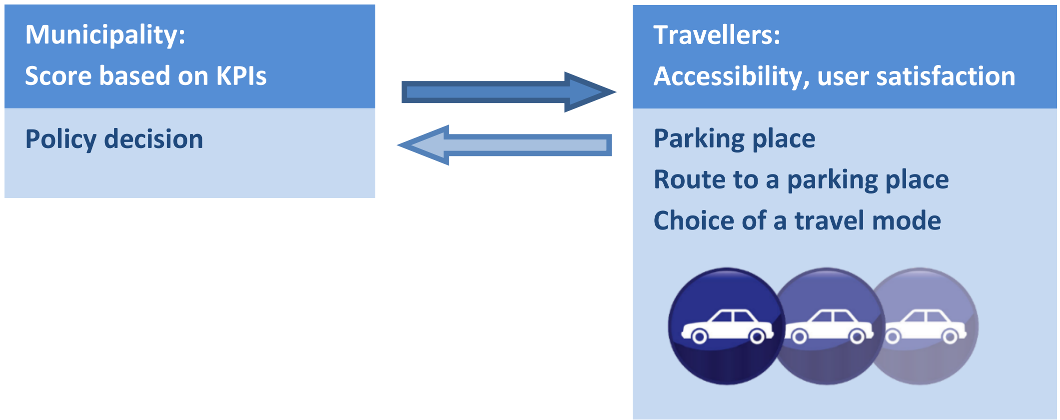


Figure 11: Decisions on parking policies as a Stackelberg game

Moreover, the relation between different mobility providers, but also other actors, represents a good example of co-opetition, which denotes the case when competitors find profitable to cooperate in certain aspect or time period or under certain conditions. For example, at the consumer level (downstream) these actors compete for market share, while at the producer level (upstream) they cooperate by sharing components, costs, knowledge, platforms, networks for mutual benefits, for instance.

Example: Decision on policies related to shared mobility

Leader: Municipality

Strategy to select: rules and conditions for shared mobility (fees, the number of released vehicles licences and other conditions)

Payoff: score based on KPIs (to be maximised)

Followers: Mobility service providers

Strategy to select: fleet design, vehicle types, price structures to maximise profit / ROI

Payoff: profit maximisation

Travellers

Strategy to select: travel mode (shared mobility and its type, walking, public transport, private car)

Payoff: accessibility (economic, operational, and physical), user satisfaction

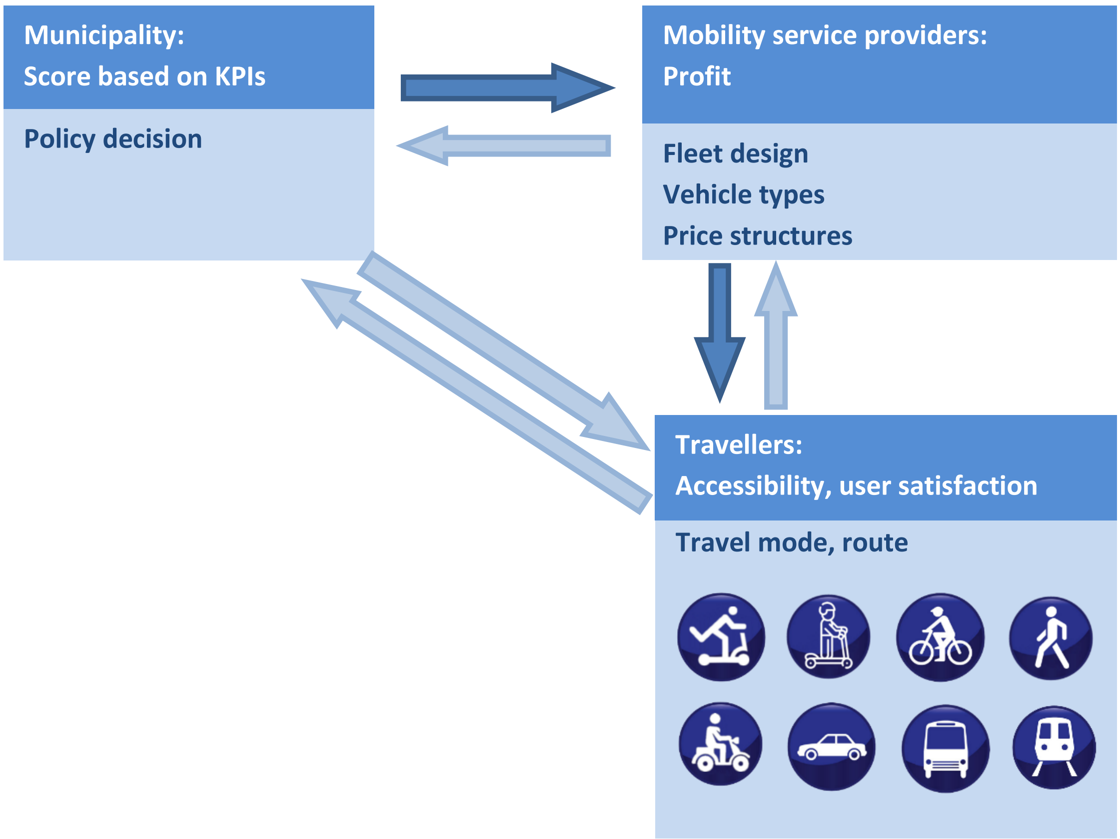


Figure 12: Decisions on policies related to shared mobility as a Stackelberg game

3.3.2.2 Fair combination of different perspectives – bargaining solution

The models that are in the background of nuMIDAS toolkit consider a municipality as an arbiter searching for the solution that would be fair for all involved parties and from various perspectives. As a “nice to have” feature, the payoff function of a municipality can be expressed by a score including weights assigned to different players (or groups of players) and also to different aspect, namely environmental, economic, and social.

For example, the use cases dealing with shared mobility may include the computation of a solution that would be optimal from the perspective of mobility providers, and also a solution optimal from the perspective of travellers. A fair solution then requires a proper conjunction of these different perspectives into a single solution, allowing a proper decision.

3.3.2.3 Social welfare function

A municipality can be viewed as a leader in a Stackelberg game. Searching an optimal strategy means the maximisation of its payoff function, which should put together different interests. Such function is usually called *social welfare function*, and there exist several approaches how to express it.

The concept of a social welfare function was introduced by Bergson (1938), whose ideas were further elaborated by Samuelson (1947), Arrow (1951) and other researchers. Even though for more than two individuals, the process of aggregating individual preferences into common social preferences faces the problems implied by Arrow impossibility theorem (Arrow, 1951), it is still desirable to determine a solution that would be admittable by all actors as fair and efficient.

For a society of N individuals whose preferences are expressed by cardinal utility functions u_i, a *utilitarian social welfare function* usually denotes the mean utility of all actors,

$$W_U(x) = \frac{1}{N}\sum_{i=1}^{N} u_i(x). \tag{1}$$

where x stands for a variable that should be optimised. For example, it can be a single-valued variable, representing, e.g., the number of vehicles in a fleet or the number of available parking spaces, a vector representing, e.g., an allocation of some resources, locations of some services etc., or a two- or more dimensional matrix representing certain configuration.

If individuals with the same utility function $u_i(x)$ are grouped together, the function (1) can be expressed in the form:

$$W_U(x) = \sum_{i=1}^{K} w_i u_i(x), \tag{2}$$

where K denotes the number of different groups and w_i expresses the fraction of individuals with the utility function $u_i(x)$. The formula (2) can also viewed as the weighted mean of utilities of K subjects.

In spite of various successful applications of this concept, it is necessary to keep in mind that it requires comparable utilities of all actors.

The so-called *Rawlsian social welfare function* is defined as the utility of the individual who is worst off:

$$W_R(x) = \min_i u_i(x) \tag{3}$$

The *Nash social welfare function* is a geometric mean of individual utilities:

$$W_N(x) = \left(\prod_{i=1}^{N} u_i(x)\right)^{1/N} \tag{4}$$

Analogically with equation (2), individuals with the same utility $u_i(x)$ can be grouped together, which yields:

$$W_N(x) = \prod_{i=1}^{N} [u_i(x)]^{w_i} \tag{5}$$

Again, it can be viewed as a weighted geometric mean of utilities of K subjects.

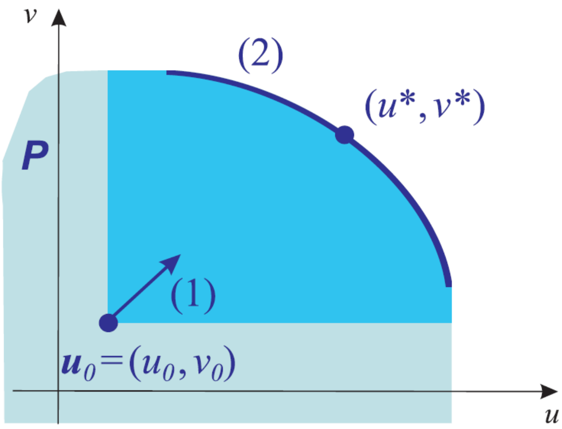
An advantage of this function lies in the fact that utilities of different groups can be of different nature, and they are not necessarily comparable. As Brânzei et al. (2017) point out, the solution based on the Nash social welfare function provides a balance between fairness and efficiency.

3.3.2.4 Arbitration problem – Nash bargaining solution

Function (5) is connected with the name of John F. Nash due to his work in the field of cooperative games and the solution of the so-called bargaining problem (Nash, 1950). For two players, Nash considered the bargaining problem as an ordered pair $(P,(u_0,v_0))$, where P denotes the set of all possible payoff pairs, so-called cooperative payoff region, and where u_0, v_0 are least guaranteed payoffs of the players. Let us denote the bargaining solution as $\Psi(P,(u_0,v_0)) = (u^*,v^*)$. Nash called for the satisfaction of the following conditions that correspond to our intuition about a fair bargaining solution:

Axiom 1 (Individual rationality)

$u^* \geq u_0, \quad v^* \geq v_0$



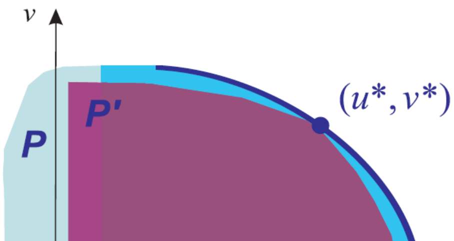
Axiom 2 (Pareto Optimality)

The pair (u^*,v^*) is Pareto optimal, i.e., there does not exist any other payoff pair $(u,v) \in P$ for which $u \geq u_0$ and $v \geq v_0$, such that at least one inequality is strict.

Axiom 3 (Feasibility)

$(u^*,v^*) \in P$

Axiom 4 (Independence of irrelevant alternatives)



If P' is a payoff region contained in P,

such that (u_0, v_0), $(u^*, v^*) \in P'$, then

$\Psi(P', (u_0, v_0)) = (u^*, v^*)$.

Axiom 5 (Independence under linear transformation)
Suppose P' is obtained from P by the linear transformation

$u' = au + b, \qquad v' = cv + d, \quad \text{where } a, c > 0.$

Then $\Psi(P', (au_0 + b, cv_0 + d)) = (au^* + b, cv^* + d)$.

Axiom 6 (Symmetry)
If P is symmetric, i.e., $(u, v) \in P \Leftrightarrow (v, u) \in P$, and $u_0 = v_0$, then $u^* = v^*$.

Nash (1953) provided a constructive proof of the following theorem:

Theorem: There exists a unique arbitration procedure Ψ satisfying axioms 1–6.

For a given bargaining problem, Nash constructed the solution to maximise the product of the utility gains

$$g(u, v) = (u - u_0)(v - v_0) \tag{6}$$

on the set of feasible and individually rational payoff pairs. Moreover, as formulated in the theorem, he proved the uniqueness of the solution satisfying the conditions 1 – 6.

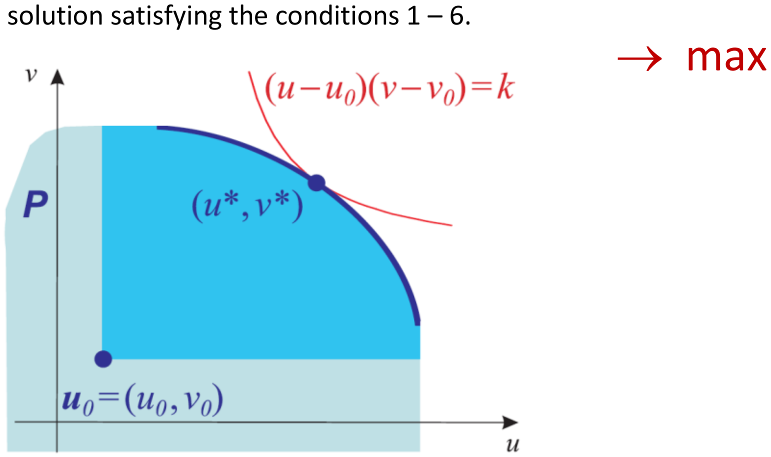


Figure 13: Construction of the Nash bargaining solution

If different importance of players should be considered, the weighted Nash solution maximises the product

$$g(u, v) = (u - u_0)^{w_1}(v - v_0)^{w_2} \tag{7}$$

For more actors/aspects, the weighted Nash solution maximises the product:

$$g(u_1, \ldots, u_N) = (u_1(x) - u_1(x_0))^{w_1}(u_2(x) - u_2(x_0))^{w_2} \cdots (u_N(x) - u_N(x_0))^{w_N} \tag{8}$$

For a coordinate system where $u_i(x_0) = 0$ for all $i = 1,2, \ldots, N$, the right side of the formula (8) becomes the social welfare function considered in (5).

4 Variables and key performance indicators

4.1 Basic concepts and principles

In an overview of existing measurement frameworks for smart cities, OECD (2020) classifies indicators, i.e., measurable variables, into three broad categories:

- **Input indicators** measure the number of resources that are allocated to a policy. Typical input indicators are the funds spent on a certain policy or the number of people working on a project. Input indicators therefore provide a measure of the effort that is devoted to pursuing a policy, but they do not give any information whether the resources are efficiently spent or whether a policy is effective in achieving an objective.
- **Output indicators** measure quantities produced by a policy in order to achieve its objectives, but not progress towards the policy objectives. Outputs are therefore means to achieve a policy objective, but no ends in themselves. Typical output indicators might show the number of motorway kilometres built, the number of people trained to fulfil a task, or the percentage of households equipped in smart energy metres. Output indicators do not tell whether a policy is effective in achieving its desired objective or not.
- **Outcome indicators** monitor the effectiveness of a policy in achieving its objectives. While outcomes are the underlying motivation behind policies, they can only be affected through the inputs and outputs. Typical outcome indicators might be the reduction in commuting time to the place of work, satisfaction with life or the city, or energy savings.

To quantify suitability and usability of proposed methods, we will concentrate on variables corresponding to output and outcome indicators, and in the end, we will identify the key performance indicators to be displayed in the dashboard of the nuMIDAS toolkit.

We consider three main categories of performance indicators, namely environmental, economic, and social. Besides basic indicators, we may propose aggregated scores allowing the determination of a position using weights assigned to these three aspects (see Figure 14Figure 6).

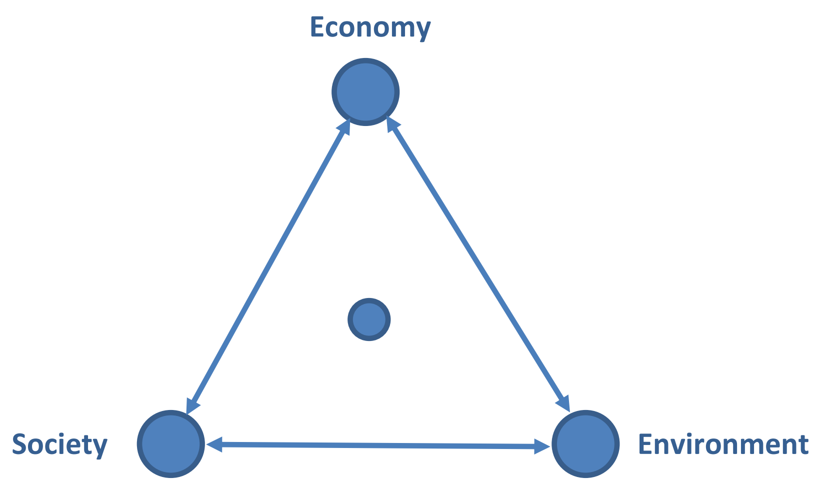


Figure 14: Balance of social, economic, and environmental aspects (adapted from (Flint, 2013))

4.2 Environmental indicators

4.2.1 Air quality – the European Air Quality Index (EAQI)

To inform citizens and public authorities about the recent air quality status across Europe, European Environment Agency (EEA) together with the European Commission's Directorate General for Environment defined the European Air Quality Index (EAQI) based on concentrations of the five main pollutants regulated in the European legislation: O_3 (ozone), NO_2 (nitrogen dioxide), SO_2 (sulphur dioxide), $PM_{2.5}$ and PM_{10} (fine particulate matter with a diameter smaller than 2.5 μm and 10 μm, respectively). For each of these pollutants, an index level ranging from 1 (good) to 6 (extremely poor) is computed separately according to its concentration in the given time interval (hour or day).[9] These levels reflecting the impact of air quality on health are displayed in Table 1. The EAQI is then defined as the maximal value of indexes for individual pollutants. It is therefore driven by the pollutant for which concentrations are poorest due to associated health impacts. For more details, see (EEA, 2022).

Table 1: European Air Quality Index (EAQI) – levels for individual pollutants (EEA, 2022)

Pollutant	**Index level (based on pollutant concentrations in μg/m³)**					
	1 Good	**2 Fair**	**3 Moderate**	**4 Poor**	**5 Very poor**	**6 Extremely poor**
Ozone (O_3)	0-50	50-100	100-130	130-240	240-380	380-800
Nitrogen dioxide (NO_2)	0-40	40-90	90-120	120-230	230-340	340-1000
Sulphur dioxide (SO_2)	0-100	100-200	200-350	350-500	500-750	750-1250
Particles less than 10 μm (PM_{10})	0-20	20-40	40-50	50-100	100-150	150-1200
Particles less than 2.5 μm ($PM_{2.5}$)	0-10	10-20	20-25	25-50	50-75	75-800

At present, the EAQI is calculated for more than 3500 monitoring stations across Europe, using a combination of up-to-date data reported by EEA member countries and forecast of the air quality level as provided by Copernicus Atmospheric Monitoring Service (CAMS). The values are available at the web page (EEA, 2022).

Different values of the EAQI are associated with health-related recommendations for both the general population and sensitive populations (e.g., children with respiratory problems, adults with heart conditions). These advices are summarised in Table 2. Figure 15 shows an excerpt of a map reporting EAQI.

[9] For O3, NO2 and SO2, hourly concentrations are used, for PM2.5 and PM10, the 24-hour running means for the past 24 hours are considered.

Table 2: European Air Quality Index (EAQI) – health recommendations (EEA, 2022)

EAQI		Recommendation	
Value	**Category**	**General population**	**Sensitive populations**
1	**Good**	The air quality is good. Enjoy your usual outdoor activities.	The air quality is good. Enjoy your usual outdoor activities.
2	**Fair**	Enjoy your usual outdoor activities.	Enjoy your usual outdoor activities.
3	**Moderate**	Enjoy your usual outdoor activities.	Consider reducing intense outdoor activities if you experience symptoms.
4	**Poor**	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat.	Consider reducing physical activities, particularly outdoors, especially if you experience symptoms.
5	**Very poor**	Consider reducing intense activities outdoors, if you experience symptoms such as sore eyes, a cough or sore throat.	Reduce physical activities, particularly outdoors, especially if you experience symptoms.
6	**Extremely poor**	Reduce physical activities outdoors.	Avoid physical activities outdoors.

Figure 15: Illustration of a map reporting EAQI (EEA, 2022)

4.2.2 Emissions

The environmental performance indicators selected for the nuMIDAS toolkit are limited to a few but important parameters, similarly as in the methodology proposed by EWI – EcoTransIT World Initiative (Schmied & Knörr, 2020). These pollutants together with the reason for their inclusion are listed in Table 3. However, the final selection will be adjusted according to available data.

Table 3: Pollutants considered by the nuMIDAS toolkit

Abbreviation	Description	Reasons for inclusion
PEC	Primary energy consumption	Main indicator for resource consumption
CO_2	Carbon dioxide emissions	Main indicator for greenhouse effect
CO_{2e}	Greenhouse gas emissions as CO_2 – equivalent. It is computed from emissions of CO_2, CH_4 (methane) and N_2O (nitrous oxide) using the formula (9)	Greenhouse effect
NO_x	Nitrogen oxide emissions	Acidification, eutrophication, eco-toxicity, human toxicity, summer smog
SO_2	Sulphur dioxide emissions	Acidification, eco-toxicity, huma toxicity
NMHC	Non-methane hydro carbons	Human toxicity, summer smog
Particles ($PM_{2.5}$, PM_{10})	Exhaust particles from vehicles and from energy production and provision	Human toxicity, summer smog

For CO_2 and other greenhouse gases emissions, the methodology formulated in the standard EN16258 for the calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers) is used. According to this standard, the calculation should consist of two steps. In the first one, the final energy consumption (litres of fuel, kWh of electricity) of each part of the transport services, so-called leg, have to be calculated. In the second step, these values should be transferred into standardised energy consumption (expressed in MJ) and CO_2 equivalent emissions (kg CO_{2e}), namely at the level of both TTW (Tank-to-Wheels) and WTW (Well-to-Wheels).

CO_2 equivalent emissions express the overall impact of the most substantial greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by the formula reflecting different effects of different gasses:

$$CO_{2e} = CO_2 + 25 \times CH_4 + 298 \times N_2O. \tag{9}$$

The concept of TTW (Tank-to-Wheels) relates to the energy consumption and emissions directly caused by the operation of vehicles, while WTW (Well-to-Wheels) also takes emissions and energy consumption related to the generation of final energy into account, as it is depicted at Figure 16. Corresponding conversion factors are listed in Table 4.

Kaparias et all. (2011) propose tonnes of CO_{2e} per capita as one of KPIs for smart cities.

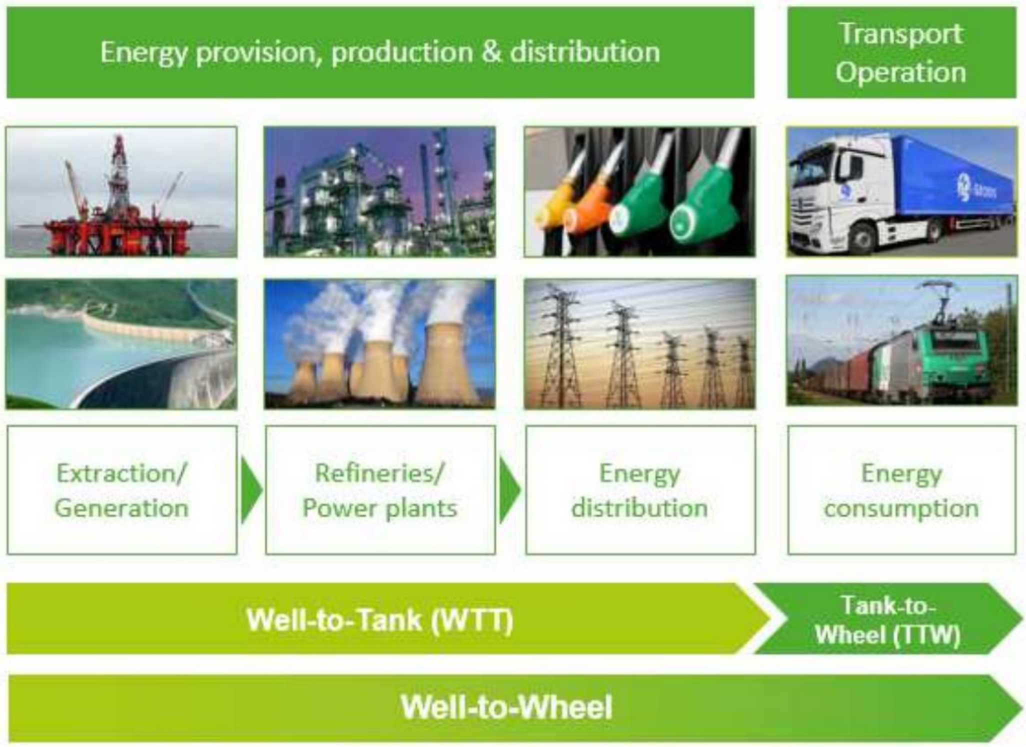


Figure 16: Graphical representation of the WTW analysis (adapted from (Schmied & Knörr, 2020))

Table 4: Conversion factors for fuels and gases (Schmied & Knörr, 2020)

Fuel	Density [kg/l]	Energy factor [MJ/kg]		CO_2 factor [kg CO_2/kg]		CO_{2e} factor [kg CO_{2e}/kg]	
		TTW	WTW	TTW	WTW	TTW	WTW
Gasoline	0.745	43.2	50.5	3.17	3.78	3.25	3.86
Diesel	0.794	43.1	51.3	3.16	3.84	3.21	3.90
CNG		46.0	51.5	2.54	2.78	2.68	3.07
LPG	0.550	46.0	51.5	3.02	3.37	3.10	3.46
LNG[10]		45.1	56.2			2.68	3.62
Bio methane[11]		45.1	50.4			0.14	0.63

[10] The EN 16258 does not contain default values for liquefied natural gas (LNG). Similar TTW values as for CNG are assumed (both fuels contain mainly methane). The WTT values are based (LBST, 2015]. The values are higher than for CNG due to higher energy intensity, especially for liquefaction.

[11] The EN 16258 does not contain default values for bio methane. Therefore, data from BioEM [IFEU 2016] was used. This data is only valid for bio methane according to the renewable energy directive (RED 2) where the use of residues is

For electricity, the value of WTW factor strongly depends on the energetic mix in the given region, and it should therefore belong to inputs for the computation. For example, the emission factor of CO_{2eq} for EU27 was CO_{2eq}/kWh.

Since the concentration of different pollutants is additive, the total index of pollution reduction can be considered as the sum:

$$I_{EM} = \sum_i w_i \cdot EM_i \,, \tag{10}$$

where EM_i denotes the emitted mass of pollutant *i*, and the weight w_i is inversely proportional to the threshold limit value for pollutant *i*. Values of weights will be specified on the basis of further research related to the third use case.

4.3 Economic indicators

For service providers, there are several metrics successfully used for the analysis of a business profitability. We will concentrate on two of them, namely operating profit, and operating profit margin, both computed is based on costs and revenues.

4.3.1 Operating costs

Operating costs include personnel costs, fuel, electricity, maintenance costs for vehicles (total or average), fleet redistribution, payment to the municipality, etc.

As Ramboll (2020) points out, all costs should be understood and transparent to the public, and they should be fairly shared between the public and private stakeholders.

4.3.2 Operating profit

An operating profit express the total earnings of a company from its core business functions for a given period, excluding the deduction of interest and taxes.[12] In general, is calculated by the subtraction of all operating expenses, cost of sold goods and depreciation and amortisation from the total revenue.

4.3.3 Operating profit margin

Operating profit margin measures profitability on a per-Euro basis. It expresses how much profit a company makes on a Euro of sales after paying for variable costs of production, such as wages and raw materials, but before paying interest or tax made from the core operations of the business in relation to its total revenues.

$$Operating\ profit\ margin = \frac{Operating\ profit}{Revenue} \tag{11}$$

It is a self-explanatory metric that can be referenced without the need for a conjunction with other ratios.

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necessary.

[12] https://www.investopedia.com/terms/o/operating_profit.asp

For service users, the economic aspect is included in the accessibility index, which combines economic, physical, and operational accessibility of a considered service, and therefore belongs primarily to the social category discussed in the next section.

4.4 Social indicators

4.4.1 Accessibility

The overall accessibility of a service includes the economic, operational, and physical aspects.

Affordability

Transportation affordability is calculated as the annual cost of transportation (based on the average cost per unit of shared-use mode and fixed costs) relative to annual income. Alternatively, it can be calculated for different income groups to assess the direction and magnitude of forecasted changes in transportation costs. Affordability therefore expresses the ability of transportation system users to pay for transportation. It puts cost in the context of income and other expenditures. The smaller share of users' incomes, the affordable the system is.[13]

The computation of affordability is based on the average cost per unit of shared-use mode as an intermediary indicator that shows the cost a user will have to pay when using the respective shared mobility mode available in the city. Together with fixed costs, it is one of inputs.

Demand

From the user's perspective, a maximal demand coverage is desirable.

Proximity

The easiness (in time or distance) to access certain service, facility, or area, especially when compared to the demand that certain solution.

4.4.2 Safety

Index of traffic accidents

Information on traffic accidents represents a convenient characteristic of the safety level of a transport network. Kaparias et al. (2011) propose the following indicator for road traffic accidents that takes into account the fact that each city has its own traffic and accident characteristics. The importance of decreasing a specific type of accidents can be adjusted by using a higher weight w. Moreover, it allows a differentiation between accidents at links and junctions to capture different impact areas of traffic management and ITS applications. For links and junctions, the accidents indexes I_L and I_L are defined as:

$$I_L = \sum_{l \in L} w_l \cdot \left[\sum_{se \in SE} w_{se} \cdot \left(\sum_{m \in M} w_m \cdot \frac{ACD_{l,se,m}}{DTV_l} \right) \right], \tag{12}$$

$$I_J = \sum_{j \in J} w_j \cdot \left[\sum_{se \in SE} w_{se} \cdot \left(\sum_{m \in M} w_m \cdot \frac{ACD_{j,se,m}}{DTV_l} \right) \right], \tag{13}$$

[13] https://www.epa.gov/sites/default/files/2014-01/documents/sustainable_transpo_performance.pdf

where the following notation is used:

w_{se} ... weight representing the importance of reducing the number of casualties in accidents with a specific severity *se* from the set of possible severity levels *SE* (e.g., uninjured, slightly injured, seriously injured or killed),

w_m ... weight representing the importance of reducing the number of casualties in accidents involving a specific traffic mode m from the set of possible traffic modes *M* (car, truck, bus, motorcycle, bicycle, pedestrian)

w_l ... weight representing the importance of link l, among the set of links *L* of the network, in terms of safety

w_j ... weight representing the importance of junction *j*, among the set of junctions *J* of the network, in terms of safety

$ACD_{l,se,m}$ ... number of casualties of severity *se* involving users of mode *m* on link *l* on an average day

$ACD_{j,se,m}$ ... number of casualties of severity *se* involving users of mode *m* at junction *j* on an average day

$DTVl$ ... daily traffic volume on link *l*

$DTVj$ ... daily traffic volume through junction *j*

Shared mobility use cases

In use cases related to shared mobility, the utilisation of available statistics is recommended. However, as Ramboll (2020) points out, they should be reported in a context, e.g., as a percentage of overall motor vehicle crashes or total number of trips. Then the public and even critics might not find the numbers so alarming. In this way, communities can be better informed and have a stronger understanding of the strengths and weaknesses of micro-mobility that should contribute to the city's overall safety goals by reducing the overall number of motor-vehicle injuries and fatalities.[14]

[14] https://ramboll.com/media/rgr/balancing-sustainable-urban-development-and-micro-mobility

4.4.3 Other informative indicators

User satisfaction

Indicators measuring user satisfaction are usually based on data from surveys. They will be therefore computed not by the nuMIDAS toolkit itself, but they can be included in a regular evaluation of a service.[15] The same holds for other indicators, as for example:

Acceptance

- Value of the system to the community
- Importance of specific infrastructure elements or policies to improve acceptance
- Clarifications between users and non-users

Compliance

- Degree of rider compliance with local regulation
- Citations issued to users for non-compliance/total rides

4.5 Normalisation of indicators and score determination

As it was discussed in section 3.3.2, each use case is considered as a Stackelberg game with municipality as the single leader, who uses the nuMIDAS toolkit as a decision support tool for selecting an appropriate policy, showing impacts of different measures, and allowing the comparison of different scenarios. As a "nice to have feature", we propose the payoff function as a score computed as a weighted geometric mean of normalised performance indexes corresponding to different aspects (environmental, economic and social to which weights w_1, w_2, w_3, where $w_1 + w_2 + w_3 = 1$, are assigned) and also to different interests of different players (weights $\alpha_1, \alpha_2, \dots, \alpha_m$ with $\alpha_1 + \alpha_2 + \dots + \alpha_m = 1$):

$$S = \prod_{j=1}^{3} \prod_{i=1}^{m} S_{ij}^{\alpha_i w_j} = \prod_{j=1}^{3} \left(S_{1j}^{\alpha_1} \cdot S_{2j}^{\alpha_2} \cdots S_{mj}^{\alpha_m} \right)^{w_j} = S_1^{w_1} \cdot S_2^{w_2} \cdot S_3^{w_3} \qquad (14)$$

Here we have denoted

$$S_j = S_{1j}^{\alpha_1} \cdot S_{2j}^{\alpha_2} \cdots S_{mj}^{\alpha_m} \quad \text{for} \quad j \in \{1, 2, 3\}.$$

The payoff function is therefore constructed in the sense of Nash welfare function discussed in section 3.3.2.2. For individual use cases, not all aspects would be considered for all players, and the computation could be simpler. But in general, the determination of the resulting score should be based on a score board such as the one displayed in Table 5.

Table 5: Key performance indicators and the resulting score – a general score board

Player	Key performance indicator	Aspect

[15] https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/147791/mobility-performance-metrics-integrated-mobility-and-beyond-fta-report-no-0152.pdf

(weight)		Environment w_1	Economy w_2	Society w_3
Player I (α_1)	**Normalised (aggregated) index 1**	S_{11}	S_{12}	S_{13}
Player II (α_2)	**Normalised (aggregated) index 2**	S_{21}	S_{22}	S_{23}
...	...	...	...	...
Player *m* (α_m)	**Normalised (aggregated) index *m***	S_{m1}	S_{m2}	S_{m3}
	Score:	$S = S_1^{w_1} \times S_2^{w_2} \times S_3^{w_3}$		

Since the geometric weighted mean is more sensitive to the change of a smaller term than to the same absolute change of a higher one, it is desirable to normalise all included indexes with respect to their range in all considered scenarios.

If a higher value of an index I is preferred to a lower one, the normalised index is computed as

$$S_{ij} = \frac{I - I_{min}}{I_{max} - I_{min}}, \tag{15}$$

where I_{max} stands for the maximal value of the considered index I obtained in the best scenario, and I_{min} stands for the minimal value of I obtained in the worst scenario (from the point of view of the index I). This normalisation method could be used for example for utilisation, profit margin, accessibility etc.

If, on the other hand, the lower value of an index J is preferred to a higher one (as for example in the case of emissions or affordability), the normalisation has to transform the index in such a way that 1 will again correspond to the most favourable scenario with $J = J_{min}$, and 0 will correspond to the worst scenario with $J = J_{max}$. The normalised index is therefore computed by the formula

$$S_{ij} = \frac{J_{max} - J}{J_{max} - J_{min}}\ . \tag{16}$$

4.6 Variables and KPIs for the nuMIDAS toolkit

The dashboard for each use case will provide KPIs to estimate or monitor the impacts of applied tools and methods. Since the tools are tailored on specific Use Cases, KPIs are also initially designed taking into account specific conditions of each use case such as requirements, policy makers' needs, data availability, etc. Nevertheless, to have a broad diffusion of the toolkit, KPIs have to be transferable, avoiding the calculation of site-specific indicators and/or indexes. Moreover, due to the lack of a standard data collection protocol, not all cities have the same amount of data and the same types of data. In this way, KPIs introduced in this deliverable, consider on the one hand data available in the pilot cities and on the other hand the possibility that these data are available in many cities.

4.6.1 Use case 1 (Pre-planning of shared mobility services)

The main goal of first use case is the determination of a fleet size of certain shared mobility service that would represent an acceptable compromise between the maximisation of the level of service and its profitability for mobility providers. The algorithm is described in detail in Deliverable 3.2. In this section we discuss how the comparison between different scenarios happens, e.g., different values of service price or operative area size.

For each specific scenario, the performance indicators given in Table 6 are computed by the toolkit. They can be sorted into categories corresponding to environmental, economic, and social aspect, and also into groups corresponding to different players with competing interests, namely shared-mobility users, shared-mobility providers, and the society as a whole. Although some indicators can be classified into more categories, the most important aspect of each indicator is selected. For example, mobility providers are supposed to consider economic aspects as the most crucial, while indicators related to mobility users are classified as social since they are used to express an overall accessibility of the service, including an economic accessibility.

A step further over the standard KPIs to be shown at the nuMIDAS toolkit for Use Case 1, a key performance indicator is selected or constructed by an aggregation as a payoff function representing his interests. For shared mobility providers, the algorithm works with the maximal value of the operating profit and provides other indicators as operating costs or expected revenue. To compare different scenarios, the operating profit margin could be selected as a convenient indicator, since it combines the information on profit and revenue, and can serve as a guide when considering an acceptable level of profitability.

$$S_{PM} = \frac{PM - PM_{min}}{PM_{max} - PM_{min}}, \tag{17}$$

where PM_{max} stands for the maximal value of profit margin obtained in the best scenario and PM_{min} stands for the minimal value of profit margin obtained in the worst scenario (regarding profit).

For society, the total distance travelled represent an information for a toolkit user, which can be used for statistical purposes and/or for an estimation of fuel or energy consumption (it types of vehicles in a fleet are known).. For the index, it is normalised as

$$S_{DT} = \frac{D_{max} - D}{D_{max} - D_{min}}, \tag{18}$$

where D_{max} stands for the maximal value of utilisation obtained in the worst scenario and D_{min} stands for the minimal value of utilisation obtained in the best scenario (regarding distance travelled).

For shared mobility users, the index of the accessibility can be used in terms of the demand coverage DC, which express the level of operational accessibility, by the formula

$$S_A = \frac{D - D_{min}}{D_{max} - D_{min}}, \tag{19}$$

where D_{max} denotes the maximal value of demand obtained in the best scenario and D_{min} denotes the minimal value of demand obtained in the worst scenario (regarding demand).

Table 6: Performance indicators for Use case 1

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Shared-mobility user	Accessibility (demand coverage)			x
	Average waiting time			x
	Average walking time			x
Shared-mobility provider	Fleet size		x	
	Operating profit		x	
	Operating costs		x	
	Expected revenues		x	
	Operating profit margin		x	
Society	Total number of trips	x		
	Total distance travelled	x		
	Fleet utilisation	x		

Table 7 and Table 8 provide an example on how the selected KPIs for all players, could be used for the computation of the overall score for the given scenario. As these KPIs already belong to different categories, it is sufficient to consider weights only for different aspects.

Table 7: Key performance indicators and the resulting score for Use case 1

Player	Key performance indicator	Aspect		
		Environment w_1	Economy w_2	Society w_3

Shared-mobility user	**Normalised accessibility** - operational			S_A
Shared-mobility provider	**Normalised operating profit margin**		S_{PM}	
Society	**Normalised distance travelled**	S_{DT}		
	Score:	$S = S_{DT}^{w_1} \times S_{PM}^{w_2} \times S_A^{w_3}$		

Table 8: Example of the score board

Player	Aggregated indicator	Aspect		
		Environment 0.33	Economy 0.33	Society 0.33
Shared-mobility user	**Normalised accessibility** - operational			**35**
Shared-mobility provider	**Normalised operating profit margin**		**45**	
Society	**Normalised distance travelled**	**53**		
	Score:	**44**		

4.6.2 Use case 2 (Operative areas analysis)

The aim of the second use case is the extension of present operative areas to maximise the level of service within each zone (sub-area of a municipality), keeping the service profitable for service operators.

For the evaluation of KPIs for scenarios of individual operative areas the tool developed for Use case 1 is used, thus the key performance indicators will be identical with those provided in Table 6 and Table 7, which can be used for the comparison of different scenarios and also for the comparison of the performance in different operative areas. In addition to these indicators for individual areas, the outputs of the second use case include the resulting definition of zones, total accessibility, and the ratio of served population.

For each mode and for each zone k, the accessibility is computed as the sum

$$A_k = \sum_j \frac{Demand_{jk}^*}{Distance_{jk}} \qquad (20)$$

taken over all zones $j \neq k$ connected to the zone k. $Demand^{*}_{jk}$ is adjusted to correspond to the considered mode on the basis of available information on modal split and average, maximal and minimal (for car sharing) trip length for individual modes. The total accessibility A is then computed as a sum of these values over all zones included in the operative area.

The ratio of served population (per mode) is a fraction

$$PR = \frac{Served\ population}{Total\ population}. \tag{21}$$

In the case that key performance indicators are used in payoff function to assess different scenarios, the normalised accessibility of Use Case 1 in Table 7 can be aggregated for a joint maximisation of both accessibility and the ratio of served population. The geometric weighted mean of both variables can be considered, as it eliminates the mutual compensation (it is not desirable to select an operative area with a high accessibility, but a small ratio or served population, or vice versa). Therefore, we maximise the value

$$S_A = NA^{w_A} \times NPR^{w_{PR}}, \tag{22}$$

where w_A, $w_{PR} \geq 0, w_A + w_{PR} = 1$, and NA, NPR are normalised values expressed as the number of percent, i.e.,

$$NA = \frac{A - A_{min}}{A_{min} - A_{min}} \times 100, \quad NPR = PR \times 100. \tag{23}$$

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Shared-mobility user	Accessibility (proximity)			x
	Ratio of served population			x
	Average waiting time			x
	Average walking time			x
Shared-mobility provider	Fleet size		x	
	Operating profit		x	
	Operating costs		x	
	Expected revenues		x	
	Operating profit margin		x	
Society	Total number of trips	x		
	Total distance travelled	x		
	Fleet utilisation	x		

4.6.3 Use case 3 (Air quality)

The third use case is aimed at the analysis of daily traffic intensity in relation to climatological, emission data, events, and other relevant sources of emissions. Moreover, it will allow to forecast air quality in a short- to medium-term basis (i.e., time horizons covering at maximum the next 10 days) and simulate scenarios for the development of future private vehicle restriction measures. The performance indicators that are expected to be provided are summarised in Table 9. For the discussion on emissions and air quality indexes see section 4.2.

Table 9: Performance indicators for Use case 3

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Society	Transportation emissions prediction	x		
	Air quality index			x

As in this use case the air quality is dependent on the transportation emissions and we assume that all players desire to achieve the same, we do not need to evaluate them from the perspective of game theoretic perspective.

4.6.4 Use case 4 (Planning for parking)

The tool developed for the fourth use case will support the assessment of impacts of on-street parking restriction policies, especially the relocation of demand for parking to adjacent areas and the increased parking searching time. The performance indicators are given in Table 10.

Table 10: Performance indicators for Use case 4

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Car user	Average searching time			x
	Availability (empty spaces/total spaces)			x
Public administration/ Parking owner	Average demand		x	
	Occupancy (occupied spaces/total spaces)		x	
Society	Average searching time	x		

For the determination of a score for the different KPIs per each player, Table 11 presents the normalised combinations. As in Use Case 2, an index of accessibility could be computed as an aggregation of indicators (see formula (22)) that express economic, physical and operational accessibility of parking for car users, with searching time, normalised according to the formula (15) and availability normalised according to the formula (16). The efficiency index, reflecting the perspective of public administration or parking space owners, could be calculated as an aggregation of indicators characterising occupancy of parking spaces and average demand (for other purposes such as parking revenues), normalised according to the formula (16). Finally, interests of the society as a whole will be represented by the index of additional traffic due to longer searching times for parking, normalised according to the formula (15).

Table 11: Key performance indicators and the resulting score for Use case 4

Player	Key performance indicator	Aspect		
		Environment w_1	Economy w_2	Society w_3
Car user	Normalised index of accessibility			S_A
Public administration/ Parking owner	Normalised index of efficiency		S_E	
Society	Normalised index of additional traffic	S_{TC}		
	Score:	$S = S_{TC}^{w_1} \times S_E^{w_2} \times S_A^{w_3}$		

4.6.5 Use case 5 (Inflows and outflows in a metropolitan area)

The main objective of the tool for the fifth use case is the estimation of in- and out-flows of a specific zone of a metropolitan area (e.g., low-emission zone) and the determination of the origin-destination matrix on the basis of data from available Automated Number Plate Recognition (ANPR) systems coupled with vehicle registration data. The OD matrix should contain the information on the origin of each vehicle, the city/district where the vehicle is registered, and the destination of each vehicle. This use case has only one performance indicator, as displayed in Table 12, thus no game theoretic assessment is necessary.

Table 12: Performance indicators for Use case 5

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Public administration	Number of trips per OD pair	x		

4.6.6 Use case 6 (Assessment of traffic management scenarios)

The aim of the sixth use case is the development of a robust methodology for assessing various traffic management scenarios, which is necessary for an active traffic management system. Considered scenarios may be based on a variety of means, such as the dynamic adjustment of traffic signal control plans, and provision of speed limit information.

Table 13 displays the first proposal of the selection of performance indicators. They will be specified during the work on the development of algorithms for this use case, similarly as the key indicators for score evaluation listed in Table 14.

Table 13: Performance indicators for Use case 6

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Traffic Management Center Operator	Traffic capacity		x	
	Flow		x	
	Occupancy		x	
	Speed		x	
	Travel time reliability			x
Public administration	Noise pollution	x		
	Total distances of vehicles driven in an area during a given time period by different types of vehicles	x		
	Fuel mix (the percentage of the share of various fuel types in a given period)	x		
	Emissions (per vehicle-km by vehicle and fuel types or by system user; total emissions for a given time period etc.)	x		
	Time losses		x	
	Queuing time		x	
	Queue length		x	
Society	Fuel/energy consumption (by vehicles or aggregated)			x
	Trip duration			x
	Waiting time			x
	Stopped time			x

Table 14: Key performance indicators and the resulting score for Use case 6

Player	Key performance indicator	Aspect		
		Environment w_1	Economy w_2	Society w_3
Traffic Management Center Operator (α_1)	**Normalised index of traffic capacity**		S_{TC}	
Public administration	**Normalised index of emissions**	S_{EM}		
	Normalised index of traffic performance		S_{TP}	
Society (α_2)	**Normalised aggregated index of travel effort** (incl. time)			S_{TE}
	Score:	$S = S_{EM}^{w_1} \times \left(S_{TC}^{\alpha_1} \times S_{TP}^{\alpha_2}\right)^{w_2} \times S_{TE}^{w_3}$		

5 Requirements on data

This chapter provides lists of the input data requirements for individual use cases.

5.1 Use case 1 (Pre-planning of shared mobility services)

Table 15: Requirements on data for Use case 1

Area	Data required
Units	Currency unit: EUR
	Time unit: minutes
	Distance unit: kilometres
	Speed unit: km/h
Expected daily demand	For each mode: Number of trips per day, but hourly demand can be defined by user
Area size	Area of the municipality (distance units at a power of 2)
Mode type	Number of modes (mode 1, ... , mode N) Specification of a mode bike / scooter / kick-scooter / car-sharing
Service types	Station-based / free-floating
Trip statistics	Mean trip duration (time units)
Finances of mobility operator	Operative costs per time unit per mode (currency units)
	Operative revenue per time unit of rent per mode (currency units)
Walking speed	Average walking speed
Fleet size boundaries	Minimum fleet size (integer)
	Maximum fleet size (integer)
Weight factor	Society weight factor (when summed with service operator weight factor must be 1)
	Service operator weight factor (when summed with society operator weight factor must be 1)

5.2 Use case 2 (Operative areas analysis)

In addition to requirements on data for the first use case, at least the following data will be needed for the second use case.

Table 16: Requirements on data for Use case 2

Area	Data required
Units	Currency unit: EUR
	Time unit: minutes
	Distance unit: kilometres
	Speed unit: km/h
Geospatial data	Metropolitan area (location, shape, attributes)
Expected daily demand	Multi-dimensional OD matrix per each mode
Population data	Population density
Mode type	Number of modes (mode 1, ... , mode N) Specification of a mode bike / scooter / kick-scooter / car-sharing
Trip statistics	Mean trip duration (time units)
Finances of mobility operator	Operative costs per time unit per mode (currency units)
	Operative revenue per time unit of rent per mode (currency units)
Walking speed	Average walking speed
Weight factor	Society weight factor (when summed with service operator weight factor must be 1)
	Service operator weight factor (when summed with society operator weight factor must be 1)
Selection of zones	Currently served zones (selection on a map)
	Mandatory zones (selection on a map)
	Excluded zones (selection on a map)

5.3 Use case 3 (Air quality)

Table 17: Requirements on data for Use case 3

Area	Data required
Meteorological data	Real-time meteorological data
	Meteorological forecast (8 days)
Emission measurements	Concentration of pollutants (NO_X, CO_2, SO_2, H_2S, CO, O_3, $PM_{2.5}$, PM_{10},...)
Traffic data	Real traffic data: counts / floating cars data Types/percentage of vehicle types and speeds over time Public transportation data
Data on fuel consumption and emissions	Statistics on fuel consumption and pollutant emissions Fuel characteristics
Events	Events relevant for pollutants emission: Alterations, road closures, public transportation incidents

5.4 Use case 4 (Planning for parking)

Table 18: Requirements on data for Use case 4

Area	Data required
Units	Distance: meters
	Speed: km/h
Spatial/geometric information	Transport network: Road segments, junctions, reference points, number of lanes, width, surface type, road numbers
Parking data	Parking supply data Parking name, location, coordinates, address, number of spots, accessibility information
	Parking demand data
Parameters	Searching speed (in speed units)
	Average length of a parking space (in distance units)
	Average Spacing Between Parking Places (in distance units)
	Policy effect expansion level
Policy restriction	Declaration of the cell(s) into which a restriction policy is enforced (selection on a map)
	New number of parking capacity

5.5 Use case 5 (Inflows and outflows in a metropolitan area)

Table 19: Requirements on data for Use case 5

Area	Data required
ANPR detections	Cameras data: Camera ID, location, latitude, longitude, street, zone ID
	Licence plates: Licence plate, time stamp, camera ID
Census data	Vehicle registration data

5.6 Use case 6 (Assessment of traffic management scenarios)

Table 20: Requirements on data for Use case 6

Area	Data required
Network	Network in shapefile[16] format
	Corridor to be evaluated
Traffic management scenarios	Traffic lights programs
	Speed limits
Traffic data	Demand profile data

[16] https://doc.arcgis.com/en/arcgis-online/reference/shapefiles.htm#:~:text=A%20shapefile%20is%20an%20Esri,and%20contains%20one%20feature%20class.

6 Conclusions

In this deliverable we summarised the findings of Task 2.4 and provided an overview of new concepts, new variables, requirements on data, and KPIs that allow for the quantification of the suitability and usability of new research methods and tools developed and analysed in Task 3.2. Task 2.4 was built upon the previous tasks in WP2, namely upon the state-of-the-art analysis of available methods and tools for various mobility services, and stakeholder and business model analysis summarised in Deliverable 2.1, and on the analysis of selected use cases provided in Deliverable 2.2.

The mobility ecosystem can be viewed as a complex system, as it comprises a large number of units where the interaction between the units results in an emergent behaviour. A useful tool used for modelling and simulation of complex systems of a distributed nature represent multi-agent systems. Multi-agent systems (MAS) can therefore be used also for the simulation of the actions of various participants in the mobility system. A standard tool for the analysis of agents' interactions and behaviour represents game theory. Based on Deliverable 2.1, where stakeholders involved in different mobility services are discussed together with the corresponding business models, we analyse different groups of actors (firms, government, customers). Their interests are often competing (costs, benefits), but they also have shared goals and contribute to the value co-creation. Different actors interact with each other and have different strategies to choose from, meanwhile their "payoffs" depend not only on their own action, but also on the action of other actors. As these interactions should be considered in decision processes, the system can therefore be modelled as a game in the sense of game theory.

The assessment of each output scenarios for the tools of each use case has implications for economy, location and intensity of various activities, environment, the quality of life and social cohesion. Key Performance Indicators (KPIs) were selected in compliance with the recommendations of Organisation for Economic Co-operation and Development (OECD) and United Nations for Smart Sustainable Cities, in addition to the capabilities of each tool and tailormade according to the needs of the municipalities.

Nonetheless, as a "nice to have" feature, a standard tool for the analysis of agents' interactions and behaviour was proposed by game theory, which also helps to aggregate different perspectives into a single solution, allowing a proper decision. Individual use cases are therefore considered as a game, namely a Stackelberg game with municipality as a single leader whose payoff function is expressed by a score based on KPIs with certain weights assigned to different players (or groups of players) and to different aspects, namely environmental, economic, and social.

7 References

Ahmed, E., Gharavi, H. (2018). Cooperative Vehicular Networking: A Survey. *IEEE Transactions on Intelligent Transportation Systems*, *19*(3), 996–1014. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8302837 (Accessed on 24.01.2022).

Brânzei, S., Gkatzelis, V., & Mehta, R. (2017). *Nash Social Welfare Approximation for Strategic Agents*. In EC'17, June 26–30, 2017, Cambridge. https://dl.acm.org/doi/pdf/10.1145/3033274.3085143 (Accessed on 26.01.2022).

Cascetta, E., Pagliara, F., & Papola, A. (2007). Governance of urban mobility: Complex systems and integrated policies. *Advances in Complex Systems, 10*. https://doi.org/10.1142/S0219525907001392 (Accessed on 13.01.2022).

EWI (2020). Environmental Metodology and Data Update 2020. Report by EcoTransIT World Initiative. https://www.ecotransit.org/wordpress/wp-content/uploads/20200828_Methodology_Report_EcoTransIT_World.pdf (Accessed on 20.12.2022).

EEA (2022). *European Air Quality Index (EAQI)*. https://www.eea.europa.eu/themes/air/air-quality-index (Accessed on 13.01.2022).

Edwards, S., & Zunder, T. (2018). *Course Syllabus. Topic Study 1: Introduction to ITS and C-ITS.* Capital e-learning platform. https://www.its-elearning.eu/assets/courseware/v1/2c2e947faa782114878b86c0231c5145/asset-v1:Capital+ITS1+test+type@asset+block/CAPITAL_WP3_ITS1.pdf (Accessed on 23.01.2022).

Engels, D. et al. (2017). *Refined CIVITAS process and impact evaluation framework* (Deliverable D2.3 of the project CIVITAS SATELLITE, H2020, Contract No. 713813). https://cordis.europa.eu/project/id/713813/results (Accessed on 02.05.2021).

Guériau, M., Billot, R., El Faouzi, N.-E, Hassas, S., & Armetta, F. (2015). Multi-agent dynamic coupling for cooperative vehicles modeling. In *Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence (AAAI'15)*. AAAI Press, 4276–4277.

Hollander, Y., Prashker, J. N., & Mahalel, D. (2006): Determining the Desired Amount of Parking Using Game Theory. *Journal of Urban Planning and Development*, *132*(1), 53–61. https://doi.org/10.1061/(ASCE)0733-9488(2006)132:1(53) (Accessed on 24.01.2022).

Kaparias, I., et all. (2011). *Key Performance Indicators for traffic management and Intelligent Transport Systems*. Deliverable 3.5 of the project Conduits, 7th Framework Programme, Contract No. 218636. https://www.eltis.org/sites/default/files/tool/conduits_key_performance_indicators_its.pdf (Accessed on 20.12.2021).

Koryagin M. (2018). Urban Planning: A Game Theory Application for the Travel Demand Management. *Periodica Polytechnica Transportation Engineering*, *46*(4), 171–178. https://doi.org/10.3311/PPtr.9410 (Accessed on 23.01.2022).

Kotsi, A., Politis, E. & Mitsakis, E. (2020). Game Theory Framework for the Coordinated Provision of C-ITS Services in Dynamic Traffic Management. *IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, 1–5.

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters, 3*, 18–23. http://dx.doi.org/016/j.mfglet.2014.12.001 (Accessed on 03.02.2022).

Lom, M., & Pribyl, O. (2021). Smart city model based on systems theory. International Journal of Information Management, 56, 102092. https://doi.org/10.1016/j.ijinfomgt.2020.102092 (Accessed on 21.01.2022).

Nash, J. F. (1950). The bargaining problem. *Econometrica, 18* (2), 155–162. https://doi.org/10.2307/1907266 (Accessed on 20.12.2021).

Pribyl, O., et al. (2021). State-of-the-art assessment. Deliverable 2.1 of the nuMIDAS project (H2020). https://numidas.eu/index.php/project-deliverables

Rufino, J., Silva, L., Fernandes, B., Almeida, J. & Ferreira, J. (2019). Overhead of V2X Secured Messages: An Analysis. *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, 1-5, https://doi.org/10.1109/VTCSpring.2019.8746479 (Accessed on 21.01.2022).

van Ruth, F. (2014). Traffic intensity as indicator of regional economic activity. *Statistics Netherlands*, 21. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.671.5907&rep=rep1&type=pdf (Accessed on 02.02.2022).

W. Saad, Z. Han, A. Hjorungnes, D. Niyato, and E. Hossain (2011). Coalition formation games for distributed cooperation among roadside units in vehicular networks. *IEEE J. Sel. Areas Commun*., 29(1), 48–60.

Schmied, M., & Knörr, W. (2020). *Calculating GHG emissions for freight forwarding and logistics services in accordance with EN 16258: Terms, Methods, Examples*. European Association for Forwarding, Transport, Logistics and Customs Services (CLECAT). https://www.clecat.org/media/CLECAT_Guide_on_Calculating_GHG_emissions_for_freight_forwarding_and_logistics_services.pdf (Accessed on 10.02.2022).

U4SSC (2017). Collection Methodology for Key Performance Indicators for Smart Sustainable Cities. Report of the United for Smart Sustainable Cities. https://www.itu.int/en/publications/Documents/tsb/2017-U4SSC-Collection-Methodology/files/downloads/421318-CollectionMethodologyforKPIfoSSC-2017.pdf (Accessed on 03.02.2022).

Appendix A Possible extended KPIs

A.1 Use case 1 (Pre-planning of shared mobility services)

Table 21: Possible extended performance indicators for Use case 1

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Shared-mobility user	Accessibility (affordability)			x

A.2 Use case 2 (Operative areas analysis)

Table 22: Possible extended performance indicators for Use case 2

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Shared-mobility user	Accessibility (affordability)			x

A.3 Use case 3 (Air quality)

Table 23: Possible extended performance indicators for Use case 3

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Public administration	Traffic flow intensity prediction		x	
	Transportation emissions prediction	x		
	Air quality index prediction			x
	Total direct CO_{2eq} emission reduction obtained	x		
Society	Traffic flow intensity		x	

A.4 Use case 4 (Planning for parking)

Table 24: Possible extended performance indicators for Use case 4

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Car user	Additional walking time			x
	Increase of parking cost			x
Public administration/ Parking owner	Difference in average occupied time		x	
	Difference in average vacant time		x	
	Parking revenues		x	
Society	Change of traffic congestion	x		
	Size of pedestrian area	x		

A.5 Use case 5 (Inflows and outflows in a metropolitan area)

Table 25: Possible extended performance indicators for Use case 5

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Transport planner	Level of service			x
	Travel time distribution of all OD pairs			x
Public administration	Revenues from congestion charge		x	

A.6 Use case 6 (Assessment of traffic management scenarios)

Table 26: Possible extended performance indicators for Use case 6

Player	Performance indicator	Aspect		
		Environment	Economy	Society
Traffic Management Center Operator	Index for traffic accidents			x
	Index for car-to-infrastructure-communication-related applications			x
	Number of network elements covered by ITS service			x
	Number of vehicles using the ITS service			x
Society	Index of accessibility			x