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Multi-agent based computation framework for evaluating the impact of plug-in electric vehicles on distribution systems

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"So, listen, to yourself and to those with whom you are speaking. Your wisdom then consists not of the knowledge you already have, but the continual search for knowledge, which is the highest form of wisdom."

[Jordan B. Peterson, 12 Rules for Life: An Antidote to Chaos]

Summary

In the last years, the distribution system changed, passing from a completely passive system (connecting the transmission system and the consumers) to an active system (where the consumers are also producers, i.e., prosumers). In this new paradigm, novel technologies are necessary for handling the large penetration of Renewable Energy Sources (*RES*). Among them, Plug-in Electric Vehicles (*PEVs*) can considered as one of the most promising for the future. A complete analysis of their impact on the current infrastructure is required, for highlighting both the positive aspects and potential drawbacks affecting the proper operation of the electrical grid. For being complete, this analysis should consider also social aspects, for emulating the behaviour of the drivers that are eventually the final users of the PEVs.

This thesis aims to develop a bottom-up model, which considers together both physical and social layers, and is based on a novel multi-agent system algorithm. The agents represent the dynamically active elements in the simulation. Each agent is described through characteristics that univocally identify it. In the proposed model, four main actions (*go home*, *go work*, *go errands*, *go leisure*) are associated with every agent in the decision layer. Four macro-sets of users are presented according to the type of employment, so there are *full-time workers*, *part-time workers*, *freelancers* and those who use the vehicle *randomly*. The description of every driver is refined through additional eleven characteristics (e.g., if he/she lives in the family, if he/she is a punctual person, etc.). The definition of the agents is closely linked to the environment in which they live (physical layer). The physical layer is characterized by three main subsets: the *electrical network*, the definition of the *city nodes* and the *road network*. Each section is described by a well-defined static structure and with its dynamic properties. The electrical system used is composed of two electrical distribution networks forming the electrical scenario of the case study. The two network samples are related to the reference city, consisting of a *semi-urban area* and a *rural area*. The two networks are supplied by two different substations and form the base layer on which city and the road network are created. To obtain the city nodes, a *clustering method* (i.e., k-means algorithm) is used to group the electrical nodes into a finite number of equivalent districts. The road network is obtained through a customized function, providing a *quadratic road graph*.

The comparison between the different case studies was made through a *sensitivity analysis*. Some parameters (e.g., the number of simulated agents and the percentage PEVs users) have been changed to evaluate their impact on the results. In one hand, we observed that for a limited number of agents compared to population estimates (i.e., 20,000 inhabitants), agents are reluctant to move towards the rural network. This result highlights the close correlation between the "social layer" and the "physical layer" . On the other hand, the increase of the population and the percentage of PEVs users affects the operational constraints of the rural network, by suggesting that the Distribution System Operator (*DSO*) should upgrade the rural network assets and change the operation of this network through novel procedures (e.g., reconfiguration). These results are the basis for further developments involving cyber and economic layers, both necessary for enlarge the share of PEVs and allowing their use as network support system.

KEYWORDS:
PEVs, RES, agent, abent-based algorythm, clustering, sensitivity analysis

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ACRONYMS	MEANS
PEV	Plug-in Electric Vehicle
DSO	Distribution System Operator
SoC	Level of energy stored in a Battery
V2G	Vehicle to Grid
ABM	Agent Based Model
TCA	Traffic Cellular Automata models
BFS	Backward-Forward Sweep method for computation Power Flow
RES	Renewable Energy Sources
CDF	Cumulative Distribution Function
DSM	Demand Side Management
DR	Demand Response
ICT	Information and Communication Technologies
PLC	Power LIne Communications

Chapter 1

Introduction

The increasing interest regarding Electric Vehicles (EVs) during the last years is essentially due to the wish of substituting of fossil fuelsin the mobility for reducing its impact on the overrall pollution emissions. In case of Plug-in EVs, they can impact on the electricity system, and the DOSs (Distribution System Operators) have to investigate how to address this important aspect. The goal of these analysis is to ensure the correct operation of the network without exceeding the value of some operational contraints. To evaluate the status of the electrical network it is necessary to know some important parameters, which are not usually known by the DSOs,such as the vehicle position and the state of charge of the vehicles. These information are owned by *PEVs* users and therefore it is not straightforward for the *DSO* to know them in advance.

1.1 Electric vehicles: perspective and vision

Recently, different well-know brands announced their engagement for increasing its number of EVs; for example Volvo announced that starting from 2019 all their cars will come with an electric engine. Volkswagen recently announced a 12 billion dollar investment in China over the next 7 years, in joint venture with the Chinese JAC, after 70 billion euros planned for electrification of European models. Another relatively new brand like Tesla, based its business on PEVs, and the market forecasts indicate that in 2019 the development of model 3 will allow the brand to overcome Porsche in terms of annual sales.

In general, car manufacturers are investing capital to try to make vehicles cheaper as fast as possible. De-carbonisation of transport is a priority of European policy, in order to reduce the emission of greenhouse gasses (up to 60 % in 2050) and improve air quality [1]. Also China has presented a full range of rules regarding the emissions and a scored program related to the electric vehicles production, putting pressure on manufacturers for driving them towards the production of EVs. The European Parliament guidelines and the National Laws guarantee a defined and stable regulatory framework, both for the standards regarding the charging points and for the public charging stations management.

All of the above aspects are summarized in Figure 1.1 that shows how the effects of the implemented policies on *PEVs* in the world.

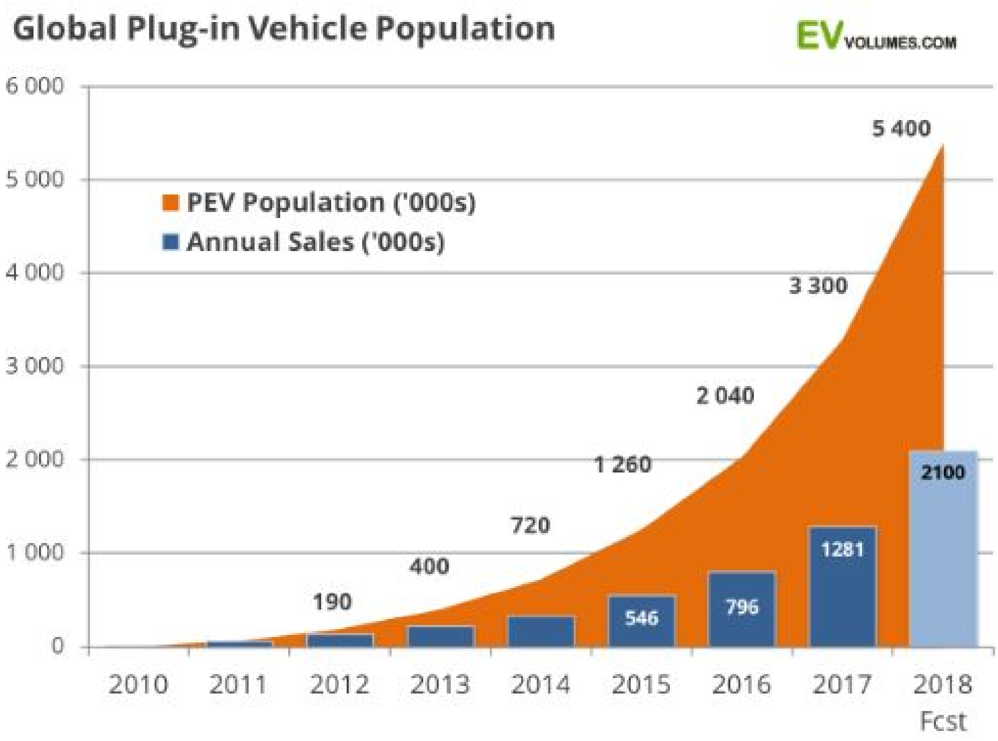


Figure 1.1: Population of EV and Annual sales

The difference between *PEV* and *PHEVS* hybrid vehicles is shown in Figure 1.2. Conventional hybrids, like the Toyota Prius, combine both a gasoline engine with an electric motor. While these vehicles have an electric motor and battery, they cannot be plugged in and recharged. Plug-in hybrid electric vehicles (PHEVs) are similar to conventional hybrids in that they have both an electric motor and internal combustion engine, except PHEV batteries can be charged by plugging into an outlet. Battery electric vehicles run exclusively on electricity via on-board batteries that are charged by plugging into an outlet or charging station. The Nissan LEAF, Fiat 500e, and Tesla Model S fall into this category, though there are many other BEVs on the market.

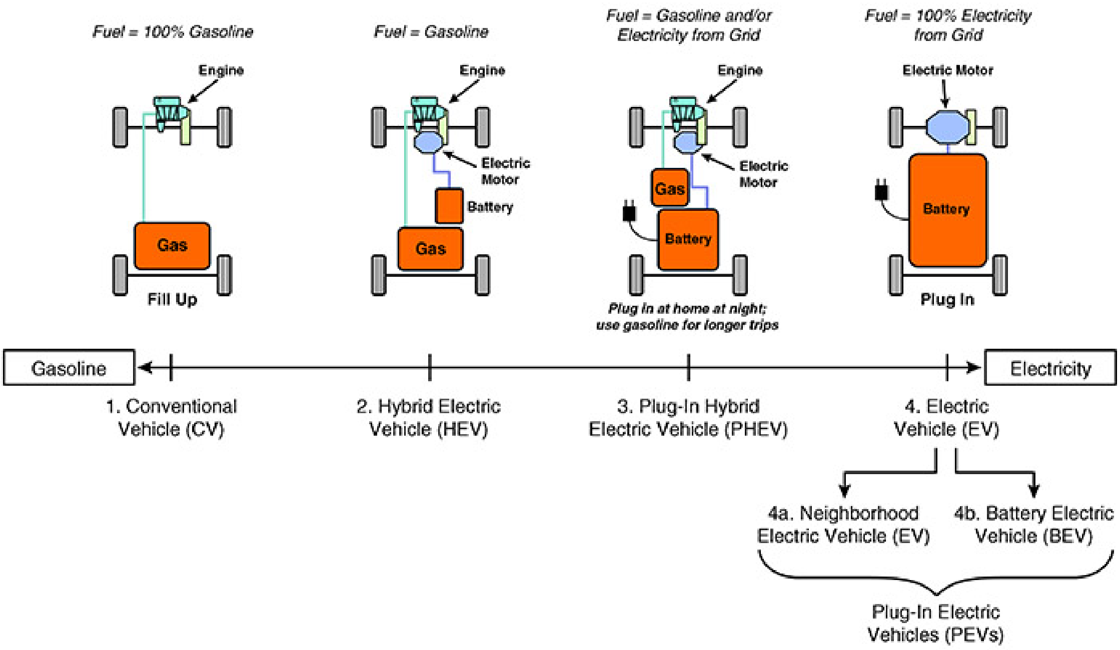


Figure 1.2: PHEV vs PEV vehicles

The development of EV technology has an impact on several levels. It is interesting to observe how even the network infrastructures (necessary for the sustainability of the system) are rapidly spreading.

The European commission has launched an observatory for the electrical mobility, the EAFO (European Alternative Fuels Observatory), where one can found some interesting data about the market growth and development on the charging systems, electric and hybrid cars [2].

The charging infrastructures (both domestic and the one available in working and public places) are essential to contribute to the diffusion and use of electric vehicles. The most interesting growth regards the charging stations with less than 22 [kW] power.

For an already advanced market, like Norway, it is interesting to analyze the preferences in the use of the charging stations, as shown in Figure 1.4. It is observed that the users' favorite charging locations are the residence and the workplace. In general, people prefer to recharge the vehicle when they have activities to do in places where the

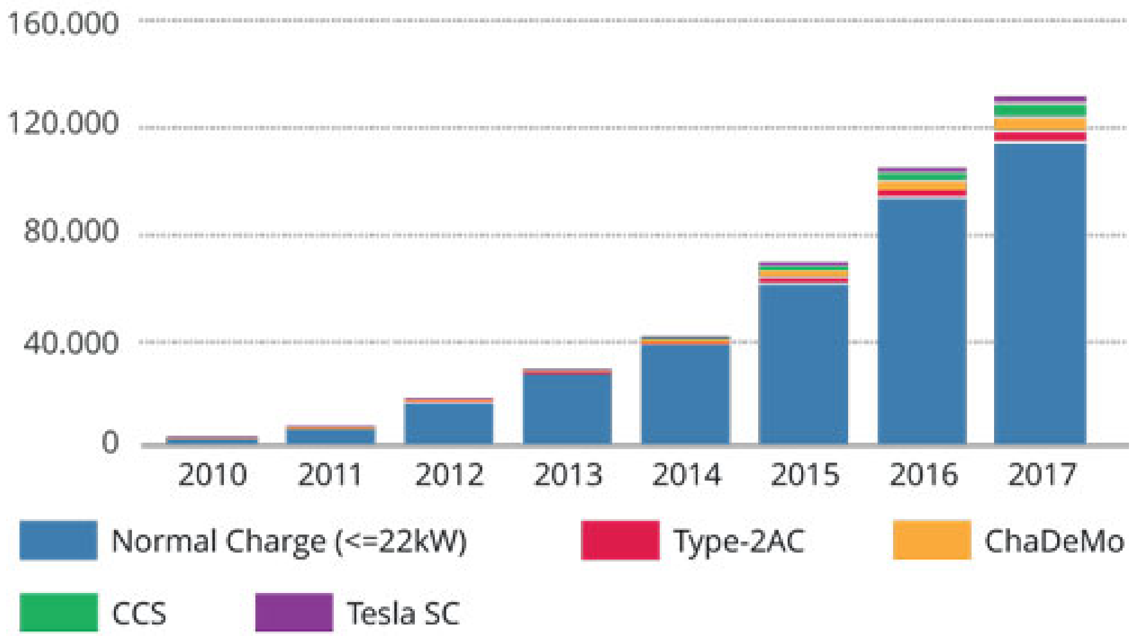


Figure 1.3: The growth in the number of charging stations in Europe

vehicle is left. As previously mentioned, the prediction of the behavior of the drivers is of fundamental importance from the point of view of the electricity grid management.

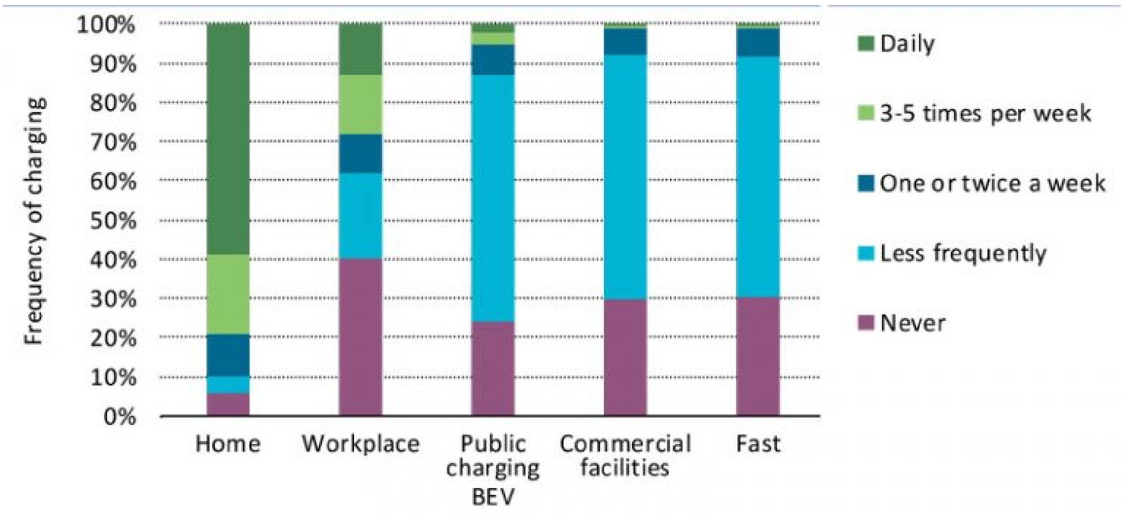


Figure 1.4: Most used charging stations in Norway

1.2 New paradigm for Distribution Network

The growing penetration of electric vehicles in society has an impact on existing network infrastructures.

The electric system is divided mainly into three voltage levels: *High Voltage "HV", Medium Voltage "MV"and Low Voltage "LV "*. The MV portion of dystribution system is responsible for supplying the aggregate zonal loads (e.g., a city district). Due to the nature of the vehicles, and to perform the recharge in a short time, this is the level of voltage at which the plug-in electric vehicles are mainly connected.

These new users connected to the network are certainly loads, because the goal of each vehicle is to have a sufficient level of energy stored in the battery, which is measured throught the State of Charge *SoC*. However, the presence of on-board electronics allows a more intelligent management of the car's own resources. Thus the concept of *vehicle to grid (V2G)* was born. Each *PEV* has three elements that allows him to operate in "V2G": a connection to the electrical network, a control system and/or a communication device that allows the network operator to access the battery and an energy flow meter.

This intelligence, the bilateral communication between the network and the vehicle, allows the network operator a better management of the distributed resources but also for the owner of the vehicle it becomes possible to earn money by selling energy back to the network.

The V2G concept was first introduced by Willett Kempton [3] who have estimated that PEV and PHEVs could provide ancillary services to transmission operators for maintaining reliability and operationals standards. They estimated the value of these electricity services up to 12 billion dollars a year, some of which would pass to V2G owners. Subsequent commercial studies have provided additional annual revenue for V2G services between $ 3777 and $ 4000 per vehicle.

From the point of view of the electricity grid, the implementation of V2G has two main advantages.

The first advantage is technical and has a strong economic impact. In fact, the electrical structures have the characteristic of being sized with respect to the maximum power values. This means that the infrastructure is mostly underutilized during normal operation. Recent studies show that load peaks occur only 80-100 h per year [4]. Because the capacity of the system remains used, a lot of the energy required by vehicles could be supported by existing infrastructure.

The second advantage is obtained with an "active"use of *PEVs*. In fact, they can be seen as distributed generators, able to compensate load fluctuations at the peaks. In addition, the battery capacities can be used to store the intermittent generation of renewable sources making it available to the grid when needed. The auxiliary services offered by the PEVs are shown in Figures 1.5. From the point of view of the distribution system, the batteries available on vehicles can serve loading requests not provided by the network operator, provide help during the hours with greater load required and help in the instantaneous balancing of demand and supply for the regulation of the frequency.

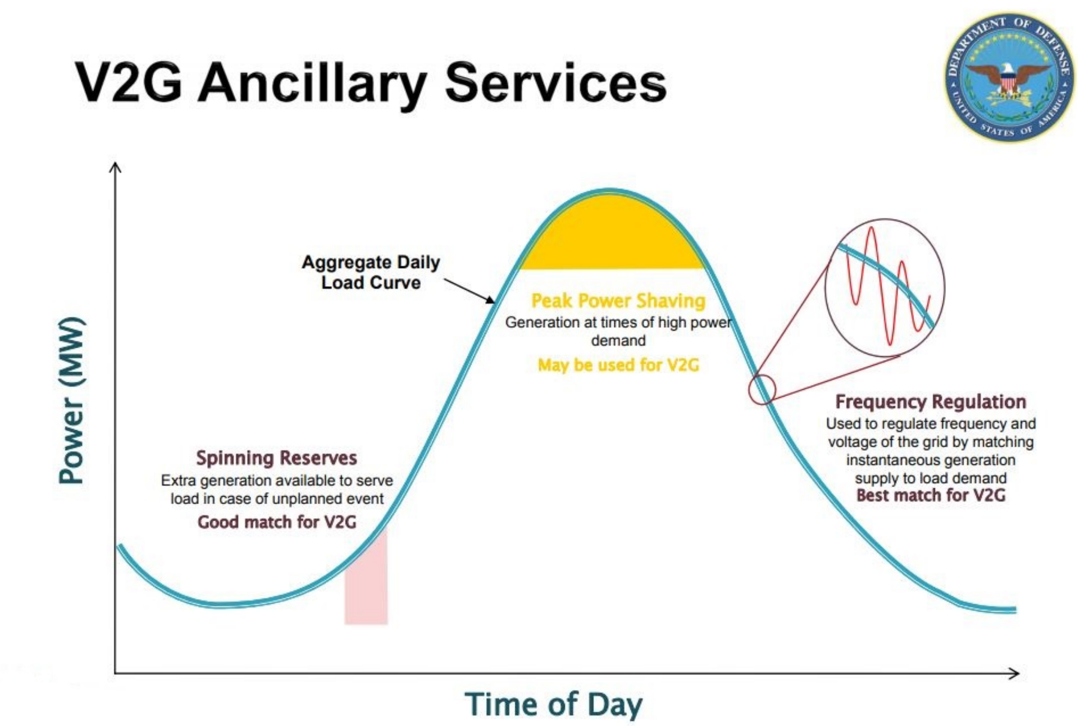


Figure 1.5: Advantage of V2G

1.3 What about Italy?

Italy, unlike many European countries, has not implemented aggressive policies to encourage the development of electric vehicles. A national law of 2012 [5] defines urgent measures for the growth of the country. The stated purpose is to favor the construction of infrastructures for the recharging of vehicles powered by electricity and the experimentation and diffusion of public and private fleets of vehicles with low overall emissions.

The availability of incentives for the purchase of cars with limited emissions had the effect of mostly increasing sales of methane vehicles.

The factors identified that led to prefer the methane-based cars compared to the electric ones are many.

- The most relevant are the lack of availability of users to invest in more technologically advanced cars
- The lack of sensitivity with respect to the air pollution
- The scarce economic means to replace the car
- The greater diffusion in Italy of cars with low displacement, diesel or methane (which already guarantee good levels of energy and environmental efficiency)
- The greater favor of the major national producer for methane cars rather than electric cars
- The lowest annual mileage of Italian motorists that does not allow to recover the advantage enjoyed by *PEVs* in terms of variable costs compared to higher fixed costs.

The delay in terms of penetration of the *PEVs* is naturally accompanied by a delay in the construction of the recharging network of the *PEVs*, in particular those of the fast type, in the negative spiral - no car, no network -.

Figure 1.6 shows how incentives in Italy were used mainly for purchasing methane vehicles (partial data for 2013) [19].

Figure 1.7 highlights the sales trend of battery vehicles in Italy and in the world (source [6]).

1.4 Outline of the thesis

The goal of this thesis is the creation of a tool capable to evaluate the impact of PEVs in distribution system, based on an algorithm able to predict the behaviour of vehicles during the day.

Different algorithms allow the study of *"complex systems"*. The thesis is based on a novel procedue used to observe the evolution of *multi-agent* systems. The algorithms based on this type of approach assume the name of *"activity-based model"* or *"agent-based model"*. These types of simulation are used in many scientific researches, with a very different purpose. In this work an ABM (*Activity-Based model*) algorithm is developed to

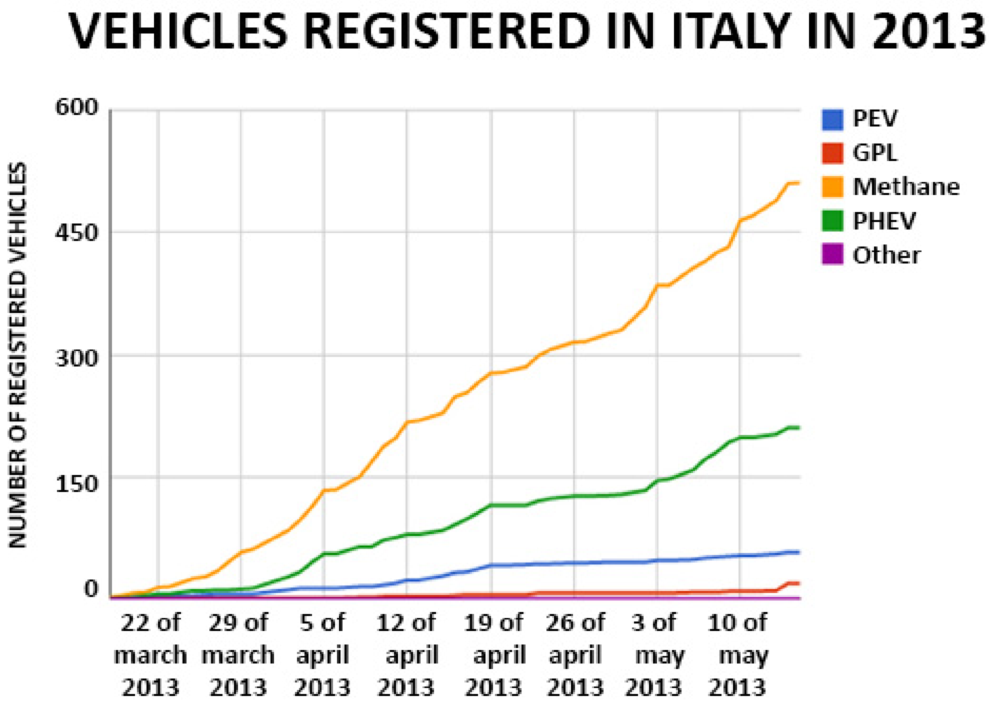


Figure 1.6: Advantage of V2G

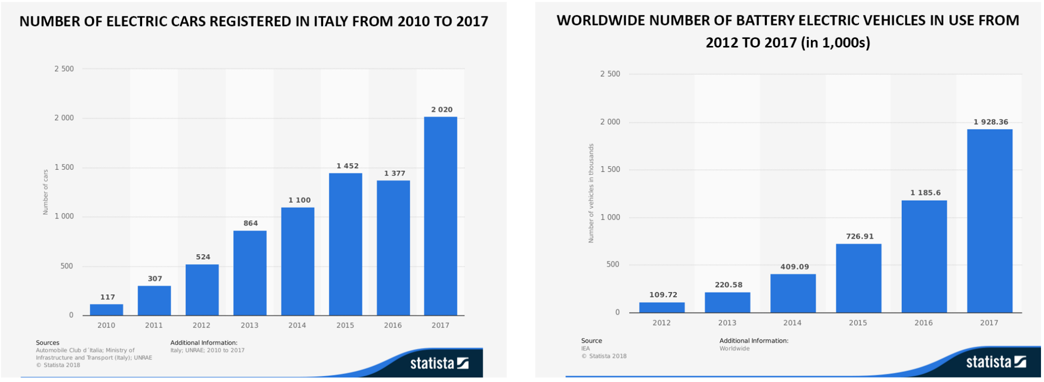


Figure 1.7: Number of EVs in Italy vs in World

characterize the typical day of a PEV driver. This approach is the basis for a *bottom-up* study of a problem described.

The thesis consists of three parts:

Background The first chapter helps the reader to know the topic covered by the thesis and provides the theoretical basis for understanding its content. The concepts dealt with in the first section are the basis on which the following chapters evolve. Previous work using agent-based algorithms and the potential of these techniques are examined. The world of transport and road networks is also described, representing the environment in which the agents move. Finally, the main characteristics of the distribution grid are shown with the management by the network operators.

Construction of the used models. In this part it is shown in detail how the problem was defined. The purpose is to provide to the reader all the knowledge to replicate the study and, once understood in detail, expand the model. It is composed of two main chapters:

- Agents Layer implementation, which presents the *"social layer"* representing the middle level in the multi-layer scheme in Fig 1.8. It describes in detail how, starting from the characteristics typical of each agent, the list of action for each agent are obtained.
- Physical Layer. This chapter describes the lowest layer of the model that represents the *environment* in which agents live. In particular, the algorithm is used to obtain a road network starting from the electric graph and the model of the electrical distribution network.

Case study implementation The last chapters are dedicated to the definition of the case study. It is described why some observed variables have assumed particular importance in the case study.

Case study implementation. Starting from the block diagram of the software it is explained how the variables to the boundary of the simulation have been defined.

A parametric analysis is then presented that allows to observe the evolution of the network variables with respect to the operational constraints. Local and global indexes are identified to describe the status of the network.

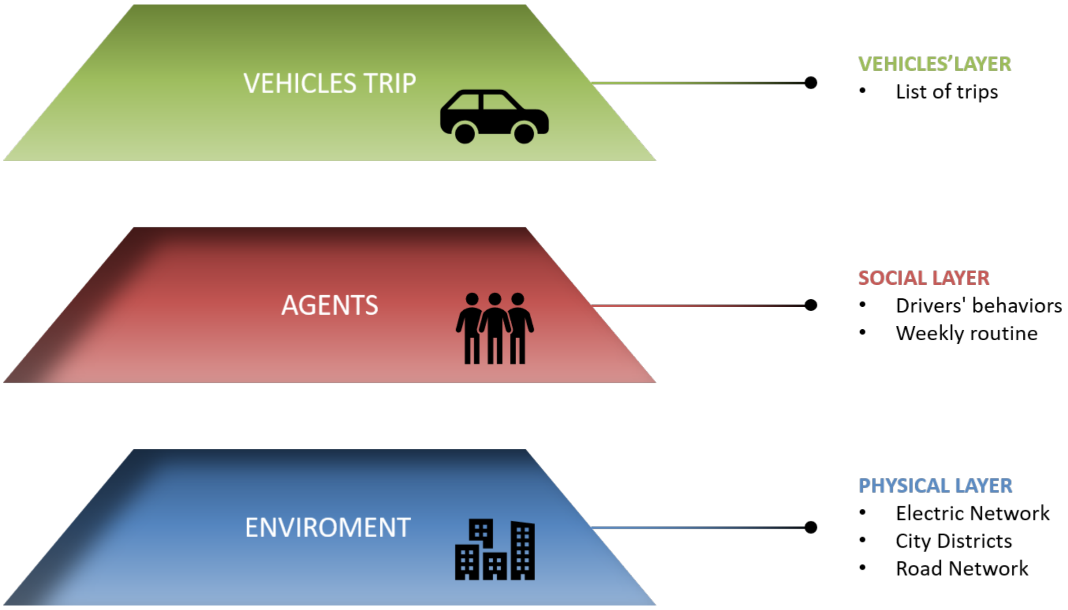


Figure 1.8: Multilayer approach of the thesis

Chapter 2

Background

The proposed chapter provides the reader with useful knowledge for who is approaching for the first time the presented models. As already shown in the chapter *Introduction*, the proposed model is of the "multilayer"type with three foundamentals layers (*environment, agents layer* and *vehicles layer*). Each layer is composed of several parts. The main parts with a theoretical background are:

- social layer (described in section 2.1)
- road layer (described in section 2.2)
- electric layer (described in section 2.3)

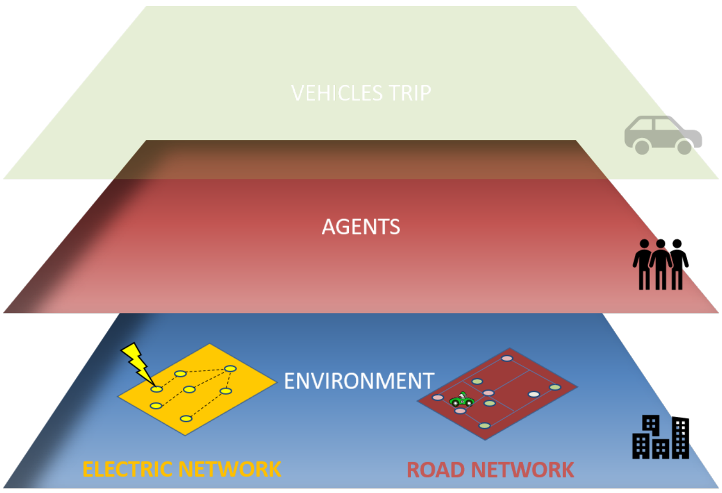


Figure 2.1: Multilayer approach of the thesis

2.1 Social Layer - Agent Based Model (A.B.M.)

Agent-Based Models are a way to approach a complex system that has been particularly successful over the last ten years.

This trend is evidenced by the growing number of articles where the so-called *"ABM"* are mentioned and the number of conferences and journals where new applications of these models are presented. Charles M. Macal and Michal J. North define these mathematical models as « third way of doing science» [7].

As mentioned, the ABM models represent nowadays the best tool for dealing with *"complex systems"*. A problem (for example the prediction of the evolution of a system), is defined as complex when the difficulty of the study is given by the big number of variables involved, rather than the intrisinc difficulty of the equations used to describe it.

A typical example of a complex system in literature is the study and forecasting of the form of a flock of migrating birds. The position that the single "agent"will take (in the example cited the bird) is determined according to its objective, but also by the interactions that it has with the other agents and with the environment.

It is precisely the possibility of defining the multiple interactions acting on the agents to make these models the right choice for these simulations. In fact, today it is easier and easier to find a large amount of raw data organized in databases and the computational effort to launch a large amount of micro-simulations is now bearable thanks to increasing computing power calculation (which was not possible until few years ago). Figure 2.2 shows the already mentioned application of the study of the flock of birds. The triangles displayed represent the agents of the system. They align themselves according to the mutual interactions and, from the alignment, determine their trajectory.

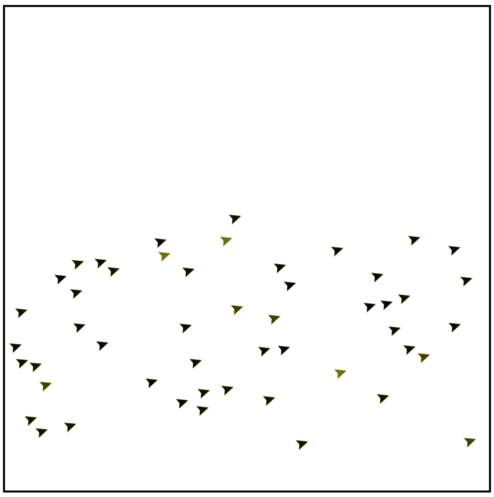


Figure 2.2: Study of a flock of birds by ABM model

2.1.1 Agent behavior

How is an agent defined? An agent definition is suggested by Macal and North in [8]. « An agent is a self-contained program capable of controlling its own decision-making and acting based on its perception of its enviroment, in pursuit of one or more objective». For a practical modeling, applied to our applications, we attribute the following characteristics to the agent:

- *self-sufficiency:* an agent is 'self-contained', unique and identifiable.
- *autonomy:* an agent is autonomous and "self-directed". Each agent can exist regardless of the presence of the other agents. He has characteristics that can be described by simple behavioral rules. The information that each agent has of the surrounding environment is provided by the interactions with the other agents and with the environment.
- *evolution:* an agent has a state that varies over time. The overall system is characterized by collective states. The behavior of each agent follows the evolution of the state. In an agent-based simulation, the states of all agents are the information the system needs to evolve from one condition to another.
- *learning:* an agent is "social"; he has dynamic interactions with other agents and consequently it is influenced and, at the same, influences the other agent behavior.

An agent has also other features:

- It is *adaptive*, for example if the global rules of simulation change.
- It is *"goal-directed"*; the goals of the single agent do not lead to maximizing the global system but each agent tends to maximize its own goal.
- An agent must be *"heterogeneous"*; each agent has several attributes that define its behaviour. Behaviours are determined by the ability to assimilate and share information. How this information is assimilated depends on the model that each individual agent has to interpret the world around it.

A typical structure of an agent is shown in Figure 2.3.

2.1.2 A.B.M. Structure

After defining what are the main logics that characterize an agent and which are today the fields in which this methodology has found greater success, the definition of this methodology is presented in detail. According to K. Ferber an "agent-based"(or "activity-based") algorithm is defined by five fundamental components [9]:

- *Environment*, representing the space where the agent moves and interacts.
- *Set of objects* with different characteristics, associated with the environment

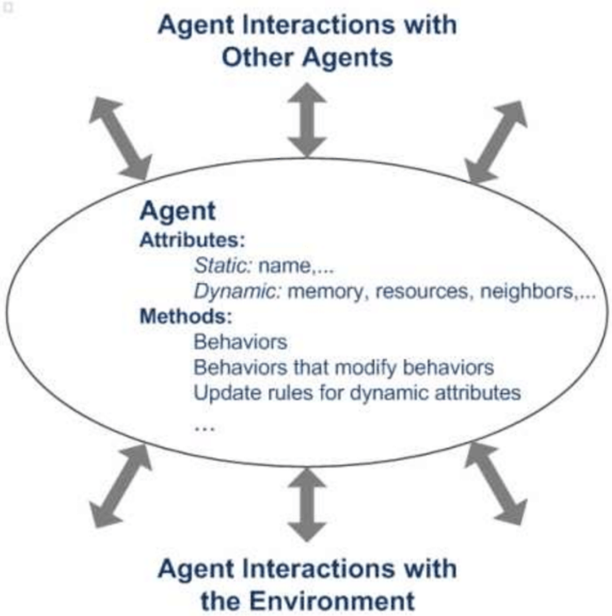


Figure 2.3: A typical agent

- *Agents*, they represent a subset of the previous object and are the active entities of the system
- *Relationships*, which link agents and objects
- *Operations*, which allow agents to perceive, produce, transform and manipulate objects.

An example of a typical structure of an activity-based program is provided by Stefano Balietti [10]. In his lessons, there is an attempt to reproduce the behavior of a flock of birds, defining five simulation steps:

- initialization
- time loop
- agents loop
- update state
- save data

Note from Figure 2.4 that there is a well-defined hierarchy among the above listed points.

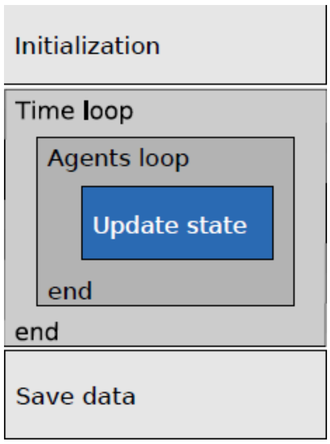


Figure 2.4: A proposed Agent-based software structure.

The criticism of the approach using the agent systems can be summarized in four main categories:

1. The risk of too *ad hoc* assumptions in the description of the characteristics of the agents
2. The failure in producing unique forecasts. In fact, in these models the concept of *path-dependence* is valid, for which small past events (even not relevant at the current time of simulation) can have significant consequences in future times.

3. The *fragility* of the results: there is no guarantee that the results are only a dependence on the initial parameters of the simulation.

4. The *replicability* of results: unlike mathematical models, the evolution of an ABM system cannot always be replicated in the same way.

However, these criticisms can be countered by saying that:

1. The assumptions are always closely linked to a preliminary theoretical knowledge.

2. Even the so-called RC models (Rational Choice) often do not have unique convergence. Furthermore, the philosophy behind the ABM is not getting univocal results, but allowing heuristic analysis and being a tool for producing large-scale mental experiments.

3. The sensitivity of the results towards the initial assumptions is a real danger for the validation of the model. However, the presence of large amounts of data collected in every scientific field, allows to calibrate the initial hypotheses with respect to reality.

4. The replicability of the results is not necessarily a problem. In fact, for a scientific analysis it is important not only to provide the results but also the codes used to obtain them. The thesis is based precisely in this perspective, allowing the reader to replicate the simulations without necessarily knowing the programming language used.

In conclusion, the choice to use this philosophy of study, aims to provide a tool for analyze future problems (in this case the impact on the electric network of battery-powered vehicles) by means of large-scale experiments. From the point of view of the writer, the ABM approaches are today the strongest tools to realistically simulate complex systems.

2.2 Road Enviroment

In the proposed model the road network represents the environment in which the drivers move and interact. The road network is represented, like the electricity grid, by a graph. The *nodes* represent a point of entry /exit of the vehicles from the streets, represented by the *branches*. A road graph, unlike the electric ones, never has radial structure. In fact, just look at the map of any city to see the high degree of meshing of the transport network.

2.2.1 Road characteristics

The elements that constitute a road graph are:

- *Node*, that is a location on a route that has the capacity to generate traffic (flow).
- *Link*, which represent the connection between two nodes where the flow occurs.
- *Route*, that is a series of connected links.
- *Network*, which is a system of nodes and links. It consist of several modal types (road, rail, etc ...), but typically consists of only single mode type.

An example of a road graph is shown in Figure 2.5. It is noted that a mesh structure with square geometry is typical.

Figure 2.5: Square geometry of the road network in Manhattan.

An agent, intended to travel from node A to node B, therefore faces with a choice that is generally independent of the choices of other agents (but may be influenced from them). In mathematics, problems of this type are described by optimization functions.

In an agent-based algorithm, an agent (called *driver*) can be defined in two ways depending on the information exchanged with the environment. A *conscious* driver receives traffic information in real time and chooses the route to reduce his stay on the road. On the other hand, an *unconscious* driver, has the previous knowledge of the roads available but does not know the traffic information real time. A distinction of these types of agents is given by Charalampos Marmaras [12].

One of the many functions developed for optimizing the path in a graph is the *Dijkstra's algorithm* [11]. The algorithm allows to calculate the travel time of each possible route (to go from A to B) and provides the best path and the relative travel time as output. The 'Dijkstra's algorithm' was first enunciated by Edsger Wybe Dijkstra (1959) and is one of the most used and discussed algorithms in the graph literature. Some modifications of the algorithm, to make it more effective in graphs with great geographical extension are presented by Rodriguez-Puente R. and Lazo-Cortes MS. [13].

The "weights"of the objective function can be the travel times of each road but also the length in km, the cost of the trip, etc. In Figure 2.6 an example of a meshed graph is shown. A travel from one node to another (e.g., from A to F) can follow different paths, each of which has a cost indicated by the value corresponding to each branch.

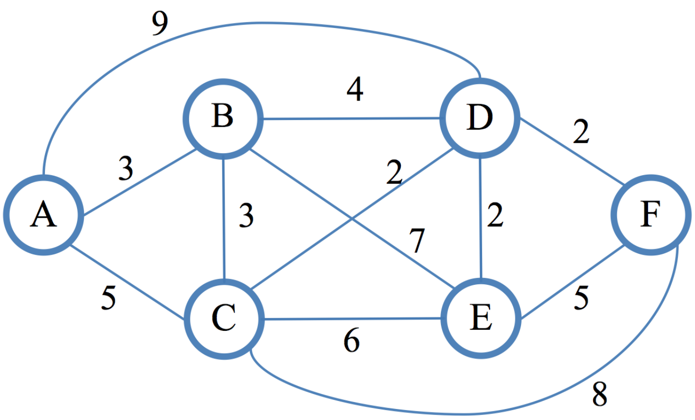


Figure 2.6: Typical example of using the Dijkstra's algorithm.

Expanding the main layers in Figure 2.7 we observe the close relationship between the road network and agents. The relationship is bi-directional because travel intentions come from below and road information and possibly traffic conditions from above.

The branches / nodes of the road graph possess some characteristics:

- They can be *Directed* or *Undirected*. This characteristic indicates the possible travel directions.

- It can be *Planar* or *Non-Planar*. In the first case there are no overlaps between roads that converge all in the nodes. In a non-planar graph the roads can intertwine with other ones. The difference between planar and non-planar graph is shown in Figure 2.8.

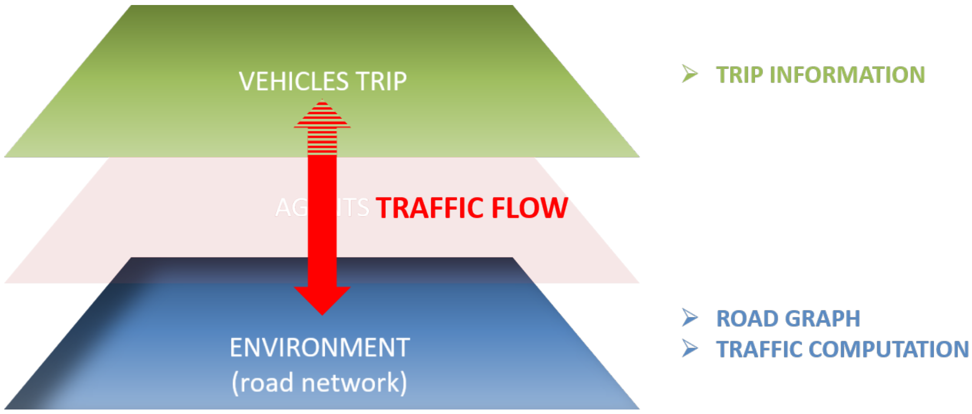


Figure 2.7: Road layer and vehicles layer communication.

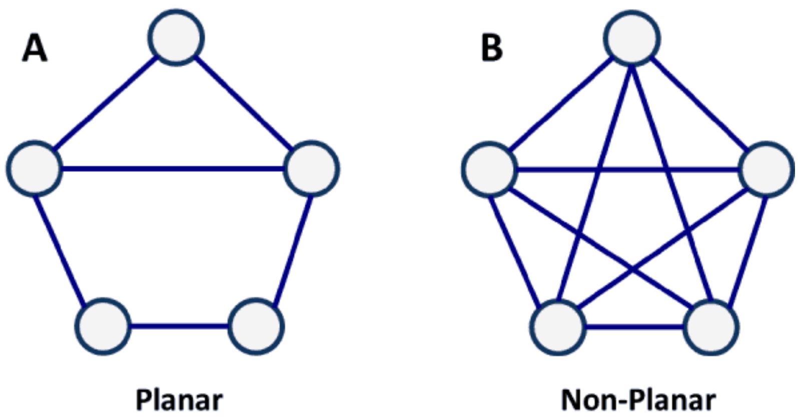


Figure 2.8: Planar vs Non-Planar network.

2.2.2 Traffic models

The description of the roads of the graph is intended to allow the addition of a traffic model in the system.

In a case study like the one presented in this thesis, it is important to make each trip as realistic as possible. Implementing road traffic is therefore necessary to increase the duration of agent journeys.

Sven Merivot and Bart De Moor proposed an overview of "Traffic Cellular Automata Models"(TCA), which are a class of methods to compute microscopic traffic patterns [14]. A proposed deterministic model (i.e., based on the real presence of vehicles on the street) fits perfectly with the agent approach of the thesis. The knowledge of the spatial position of each agent (in every time) is in fact a prerogative of the ABM approach.

The average speed of each road segment is calculated based on the exsisting number of vehicles. As the volume of traffic increases, the model leads to congestion, a situation in which the speed is not zero but is a very low value. The criticality of this model is the assumption that each vehicle proceeds at the same speed along the entire road (i.e., the speed computed by the model). A vehicle entering one end of the branch thus influences the speed of a vehicle entering from the opposite node in the opposite direction.

The roads are described by three basic parameters:

- u_f[km/h] - is the average travel speed without traffic
- k_c [veh/km] - is the number of vehicles needed for solving the traffic
- k_j [veh/km] - is the number of vehicles that congestes the road

The parameter q represents the density of vehicles on the road.

Based on the proposed model, every vehicle on the road influences the speed of other vehicles on the same road. In the agent system it is possible to obtain in every moment the position of all vehicles, that is the input for the traffic model.

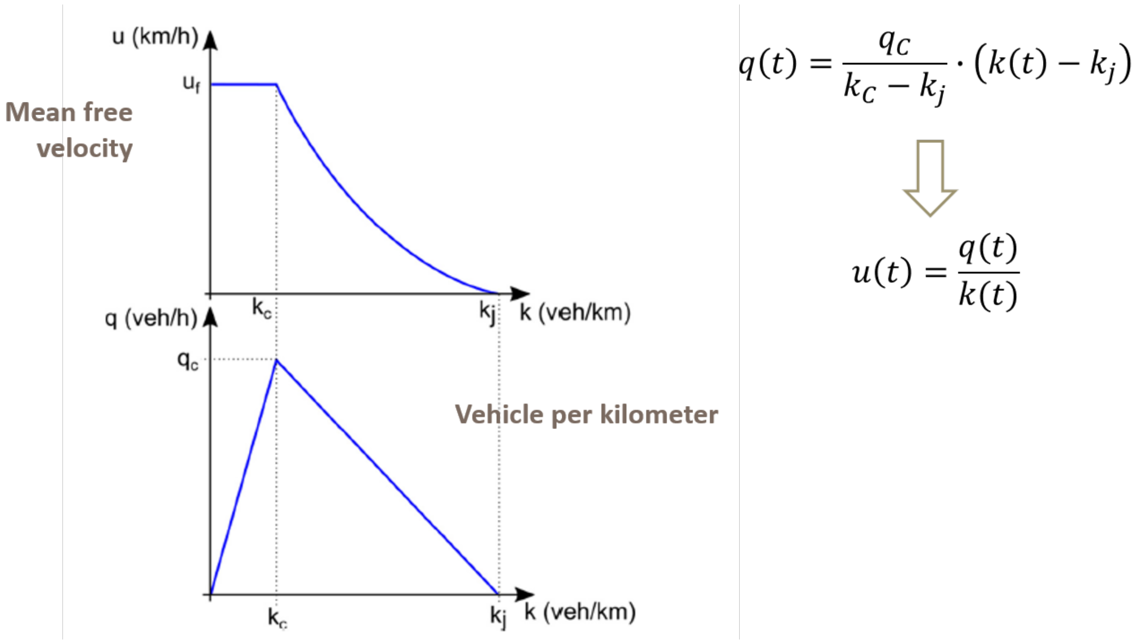


Figure 2.9: Maerivoet and De Moor deterministic traffic model.

2.3 Electrical Environment

The electrical network in the diagram of Figure 2.1 is a part of the *Environment*. In reality, an evolution of the model would lead to the creation of two additional layer, the *Economic layer* and the *Cyber Layer*; they would be at the top in the layer structure of this thesis. The electrical layer in this thesis is the one in which the most analytical analysis is carried out. It can therefore be defined as a mathematical layer.

It represents the electricity distribution system. In general, the electricity grid is divided into three levels connecting the production plants to the users. In Italy, the *HV* network (V> 30 [kV]) is known as the *Transmission network* and is the backbone of the system. It is owned and managed by Terna and has a length of over 63,500 km. It has a mesh structure (with multiple paths between one node and another) and connects the production plants (input points) with the primary substations. The network broadly covers the entire National territory and also has the function of interconnecting the National network with the European electricity grid, to optimize production according to needs and to reduce the effect of a malfunction of power plants and lines.

The *MV* and *LV* networks ($1 \leq V \leq 20$ [kV]) are called *Distribution system*. In the primary substations (HV/MV) there is a transformer that operates from high to medium voltage (10 [kV] - 15 [kV] - 20 [kV]) and here begins the distribution network which represents the last part of the electricity supply chain for the delivery of electricity to finals users. The management of this network is carried out by the *DSO* (Distribution System Operator) which continuously checks that the power flowing in the network does not create technical problems. Some users of particularly large sizes (the parking lots of PEVs vehicles for example) are connected directly to the MV nodes. The MV network, in Italy, is managed through a "natural monopoly"and has a weakly meshed structure with radial operation. The *LV* system ($V < 1$ [kV]) carries the electricity to the users (e.g., domestic) in a capillary way.

The structure of the National electricity grid and the respective voltage levels are shown in Figure 2.10.

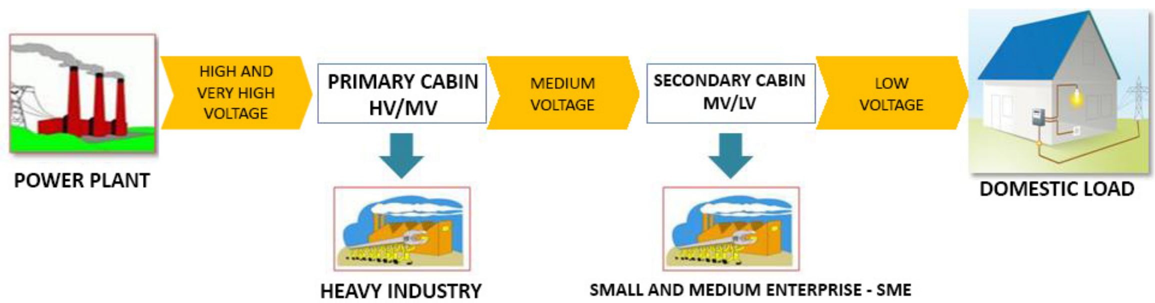


Figure 2.10: Levels of Voltage and national networks.

2.3.1 Distribution Network Structure

The electric system is represented by *graphs*. A graph is composed of:

- *Nodes*, representing the input/output points of the power, in its path from the generators to the users. Some network nodes are automated and controllable remotely from a command center by network operator (DSO for distribution system).
- *Branches*, representing the connections between two nodes. Classic examples of branches are electric lines and transformers.

A typical electrical graph has three possible structures:

- *Meshed graph*: as mentioned above, is the structure used for the transmission network (HV). It means that the power flow between two nodes can follow alternative routes (the power flow, following the rules of basic electrical engineering, is divided according to the impedances of the branches).
- *Radial graph*: it is the structure used for LV networks. There are no loops and the graph is called *tree*. Each node is connected to the others via a single path.
- *Weakly meshed graph with radial operation*, is the structure adapted for the MV system. This structure exploits the simplicity of the logic of radial network protections and allows, if necessary, a reconfiguration of the network. This possibility permits, in case of failure and consequent opening of a branch, to do not leave a portion of the network disconnected, where perhaps there are privileged loads

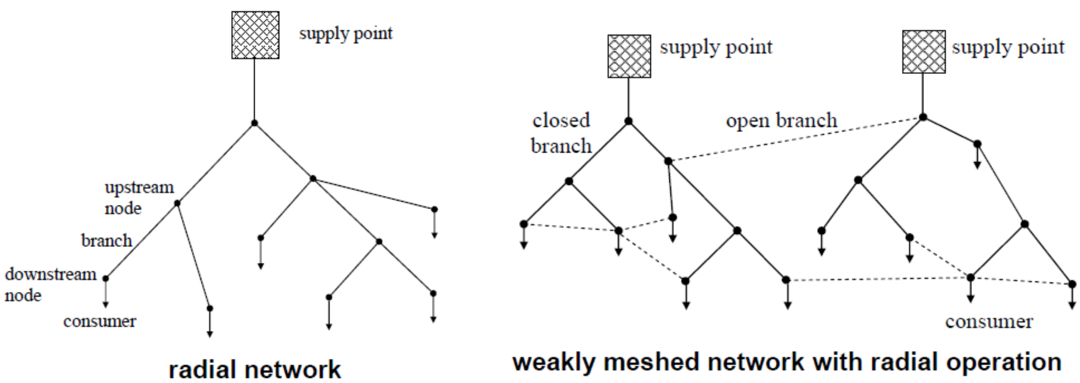


Figure 2.11: Radial network vs weakly meshed network [18]

Advantages of a radial network

The main advantage of operating with a radial network is of economic nature. In fact, in a "traditional"network where the power flows are unidirectional (from the HV/MV substation to the loads), only one automatic protection (circuit breaker) is needed to guarantee protection. The circuit breaker is a very expensive device (its price increases significantly with the size) which is able to detect violations of network constraints and open the circuit. Radiality is therefore a fundamental characteristic for the distribution network. A weakly meshed network allows the network operator to choose which branches to leave open, reserving them for second puroposes. The selection criteria may be different, for example the goal may be to find the configuration that minimizes the total network losses (reduce operating costs), etc. In radial configuration it is also relatively simple to calculate the power flowing on each branch.

In a radial network the flow of power towards a generic node (e.g., towards the fault) is unidirectional. The procedure for putting offline the faulty network portion is therefore very simple. After the circuit breaker opens, the branch to be disconnected is detected to isolate the fault. Manually (or telematically) the branch is opened by means of a simple switch (much cheaper than an automatic circuit breaker) and the network can be re-energized. Obviously, there are procedures to identify self-extinguishing faults and to accurately detect the point of failure but are not relevant for this thesis.

2.3.2 Distribution Network Analysis

To compute the status of the electrical grid in terms of node voltage and current in the branches we need the knowledge of multiple parameters:

- *Knowledge of the structure of the distribution network.* There is a matrix-based representation that allows a synthetic description of the relationship between nodes and branches.

- *Knowledge of the parameters of the network*, i.e., impedances/admittances of the branches, lengths, etc.

- *The knowledge of loads connected to the network.* The thesis jas the perspective to be a tool to predict possible load scenarios. In fact, although with an aggregated vision, some types of loads have the characteristic of being strongly unpredictable in time and space. Battery-powered vehicles connected to the network are included in this type of loads. An 'agent-based' approach arises as an alternative to the more classical models with probabilistic loads.

The goal of the analysis is to determine:

- the voltage in each node (module and phase)

- the current on each branch

- losses on each branch

- the enforcement of network constraints imposed.

In case of violation of network constraints, the response of the network operator may be to act on one of the reconfigurable nodes (e.g., by acting on the turns ratio of the HV/MV transformer), it may decide to reconfigure the network or in the future dispatching the flexible resources existing (for example by V2G).

Matix-based distribution network representation

Taking the graph of Figure 2.12 as an example, we define a matrix **L**, called *matrix of incidences*. The matrix **L** indicates the relation between nodes and branches. The rows of the matrix correspond to the branches of the network, the columns to the nodes. Reading the matrix by rows, the value $+1$ is insert in correspondence of the initial node of the branch, and the value -1 at the final node position.

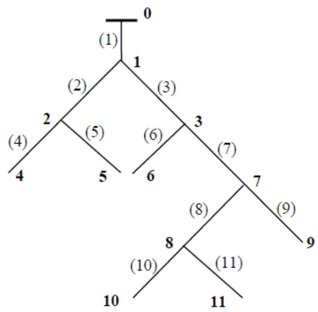


Figure 2.12: Radial graph example. [18]

From the point of view of the calculations, the matrix *Gamma* Γ, inverse of the matrix of incidences, is even more important. The matrix Γ can be constructed visually from the network and can be read by rows or by columns. Reading by rows (i.e., nodes) it shows which branches connect the node to the HV/MV node (*slack node*). Reading for columns (i.e., branches) indicates which nodes would remain disconnected by opening the branch under analysis. The reading of the matrix by columns is particularly powerful, as it allows to derive the current in the branches as the sum of the currents of the underlying nodes.

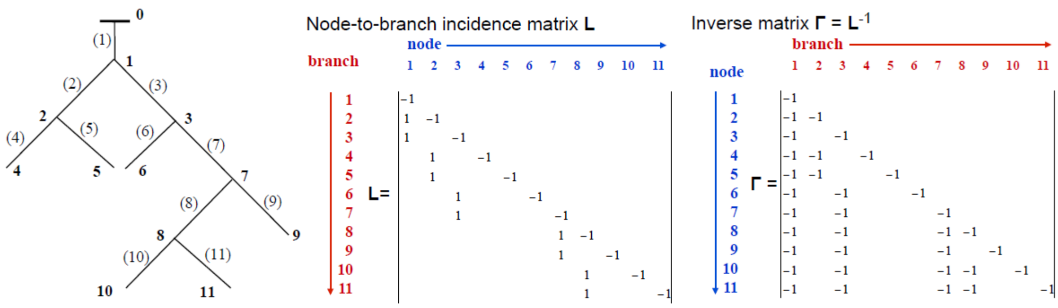


Figure 2.13: Matrix description of the graph. [18]

Backward Forward Sweep: a method for distribution network analysis

For radial networks, an iterative calculation method allows obtaining the objectives of the analysis. One of the possible methods is the *Backward-Forward Sweep* (*BFS*). The algorithm is now presented in its simplest version, when the studied network is balanced. A balanced three-phase system is easily assimilated by an equivalent single-phase system. In a MV distribution system, the hypothesis of balanced loads is plausible. The analysis takes place in two different parts: the *backward phase* and the *forward phase.* The two calculations are repeated in an iterative manner until the convergence of the results is reached.

BACKWARD STAGE: fixed nodal loads and voltages all the complex currents absorbed by the nodes are calculated. A load in node i can be described at assigned impedance $\bar{Z}_{\mathrm{i}}$ or at assigned power $\bar{S}_{\mathrm{i}}$. In both cases it is easy to calculate the current absorbed ("shunt") $\bar{I}_{\mathrm{Si}}$, note the $\bar{V}_{\mathrm{i}}$ (first iteration $\bar{V}_{\mathrm{i}} = 1$ pu). Note all the nodal currents and the matrices that describe the network, it is easy to calculate the vector containing the complex currents on all branches $\mathbf{i_B}$ and the vector containig the complex current on all nodes $\mathbf{i_s}$:

At iteration k:

$$\begin{cases} \bar{I}_{\mathrm{Si}}{}^{(\mathrm{k})} = \bar{V}_{\mathrm{i}}{}^{(\mathrm{k\text{-}1})}/\bar{Z}_{\mathrm{i}} & \text{for the impedance-specified load at node } i \\ I_{\mathrm{Sh}}{}^{(\mathrm{k})} = \bar{S}_{\mathrm{h}}{}^{*}/V_{\mathrm{h}}{}^{*(\mathrm{k\text{-}1})} & \text{for the power-specified load at node } h \end{cases} \tag{2.1}$$

$$\mathbf{i_B}^{(\mathrm{k})} = \Gamma^{\mathrm{T}} \mathbf{i_S}^{(\mathrm{k})} \tag{2.2}$$

FORWARD STAGE: The currents in the branches allow to evaluate the voltage drops and to recalculate the nodal voltages again, proceeding *forward* from the root to the load terminals. The vector $\mathbf{v}$ contains all complex voltages.

$$\mathbf{v}^{(\mathrm{k})} = V_0 \mathbf{1} - \Gamma \mathbf{Z_B} \mathbf{i_B}^{(\mathrm{k})} \tag{2.3}$$

The procedure is iterative and is interrupted when the voltage variations from one iteration to another are lower than a threshold called ϵ.

$$max_{\mathrm{i}}\{\frac{|\bar{V}_{\mathrm{i}}{}^{(\mathrm{k+1})} - \bar{V}_{\mathrm{i}}{}^{(\mathrm{k})}|}{\bar{V}_{\mathrm{i}}{}^{(\mathrm{k})}}\} < \epsilon \tag{2.4}$$

2.3.3 Distribution Network Communication - CYBER LAYER

The topics covered in this section are not relevant to the work done in the thesis but from an engineering point of view it is interesting to investigate the penetration of telecommunication tools in distribution networks.

As mentioned, the implementation of a *Communication layer* would represent a natural development of the proposed model. In fact, especially in view of the exploitation of resources distributed on the network (e.g, PEVs), the communication between the system operator (DSO) and vehicles would allow an intelligent balancing of supply and demand. The addition of the technology of the telecommunications sector (*Information and Communication Technologies - ICT*) is central for the concept of *smart grid*. In this new paradigm, the presence of distributed resources (e.g, renewable sources, *RES*) makes it difficult to balancing demand and production of power (*RES* are characterized by a large variation in production levels). Demand-side-management (*DSM*) and demand response (*DR*) are increasing their importance to maintain the operation of the network economically viable, without the need for excessive investment on the various existing network levels (designed for a unidirectional flow from large production centers to end users). The research, to date, identifies in the distribution network the first step for the transition from the old paradigm to new [20].

At the heart of the smart grid concept there is the convergence of information and communication technology with power engineering. Monitoring, analysis, control and communication capabilities are added to the existing network infrastructure, to obtain more accurate information on the current status of the network and use this knowledge to manage it more efficiently. This last aspect has today great importance from the point of view of the imposed environmental constraints, at the base of the evolution of the intelligent network.

Figure 2.14 shows the convergence of communication and information technology with the power systems engineering [21].

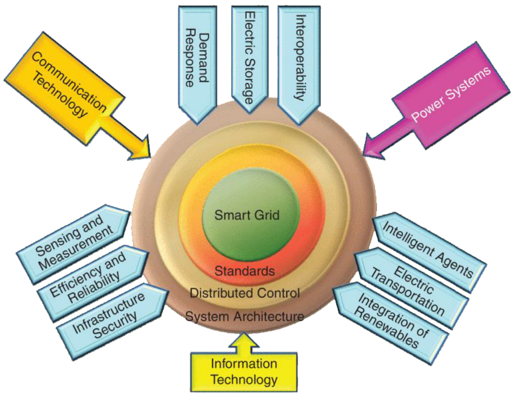


Figure 2.14: Basic smart grid ingredients.

ICT technology therefore plays an important role in the development of smart grids. Some performance indicators and communication requirements are:

- *latency requirements*, which indicate the time required to send data from one point to another. For applications such as real-time estimation of the network status, these parameters are fundamental and a very low value (tens of ms) is required; for the collection of smart meter data, instead, the required times are not critical (up to seconds)
- *speed requirements* (*data-rate*), i.e., the volume of data that can be sent in a certain time. For example, video monitoring and control data of an area require high data transmission speed.

- *reliability requirements*, i.e., the ability of the communication system to remain available to send data. Application of remote protection systems have very high requirements.
- *security requirements*, these are multiple requirements (e.g., confidentiality, integrity, availability, etc.) and have the objective of protecting the system from a wide range of attacks.

The so-called *"Power Line Communication"(PLC)* uses the existing wiring of the power network for sending data packets. In this way the electrical network also becomes the communication network. There are different types of PLC [22] networks such as ultra-narrowband (300-3000 Hz) communications with very low bit rates (100 bps) or broadband technologies with data transmission up to 200 Mbps. The criticality of this approach is given by the use of the traditional electricity grid, not designed for this purpose.

The typical architecture of a model integrating ICT and power system is shown in Figure 2.15.

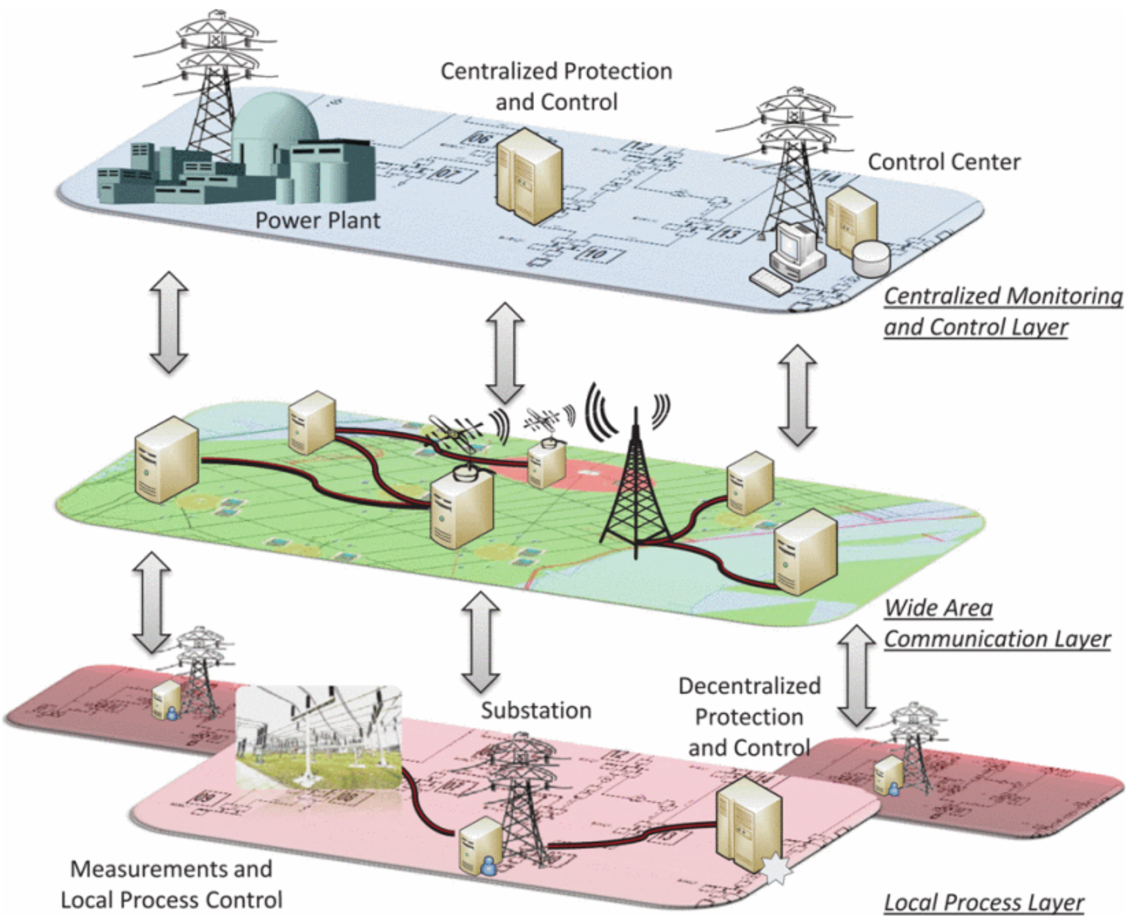


Figure 2.15: Integration concept for ICT and power systems.[22]

2.4 Similar work in literature

Given the growing trend in the sale of battery-powered vehicles (EVs), also known as plug-in electric vehicles (PEV), the network infrastructures for vehicle charging are multiplying (see the *Introduction* chapter).

The impact of reloading the PEVs on the existing distribution network is not yet fully investigated.

For example, in [15] the authors focus their attention on the sensitivity of agent-based models on price signals that can be sent from a centralized unit. Using four points of aggregation they studied the evolution of the system in the presence of *dumb charging*, *two-rate time-of-day tariff* and *smart charging*. The results of the scenario indicate that the aggregated profiles in the "hubs"are worse in the presence of a two-hour rate (applied for example to domestic users) and that the centralized and "intelligent"management is the most effective from the point of view of the network.

In a study by Yingyun Sun and Wei Tian [16] vehicles use is optimized to reduce the operating costs of the network. At the same time, optimization of travel departures reduces traffic congestion.

The article that inspired the thesis is the already mentioned [12]. Its micro-network formed by eight nodes integrates the model of traffic used with the electricity grid. The focus of the study is the comparison between aware and unaware users, compared to the use of public charging stations present in the nodes. Agents move randomly across the road network based on randomly extracted destinations and do not have detailed descriptions. In this study, electrical and road nodes coincide and in each of these nodes it is possible to recharge the vehicle. The structure used in this study is shown in Figure 2.15.

The thesis is an attempt to replicate what was read, expanding it with wider and more detailed road network. Moreover, the possibility of using electrical test networks used at Politecnico di Torino makes the case study much more realistic than any other model seen.

The thesis differs from all the articles read for the linear structure, in which each described layer is recognizable. From the theoretical study of the characteristics of each level to the realization of the models, the interactions between the different parts of the program are always understandable and recognizable. In fact, the goal has been from the beginning to bring together different technologies and concepts in a single environment. To do this it is essential to know what are the inputs and outputs of each proposed layer, to make their coupling compatible. Once you have entered this point of view, you realize that it is easy to cohabit even different areas (e.g., traffic patterns and studies of power flows) and open up countless ways to develop and make the proposed model increasingly global .

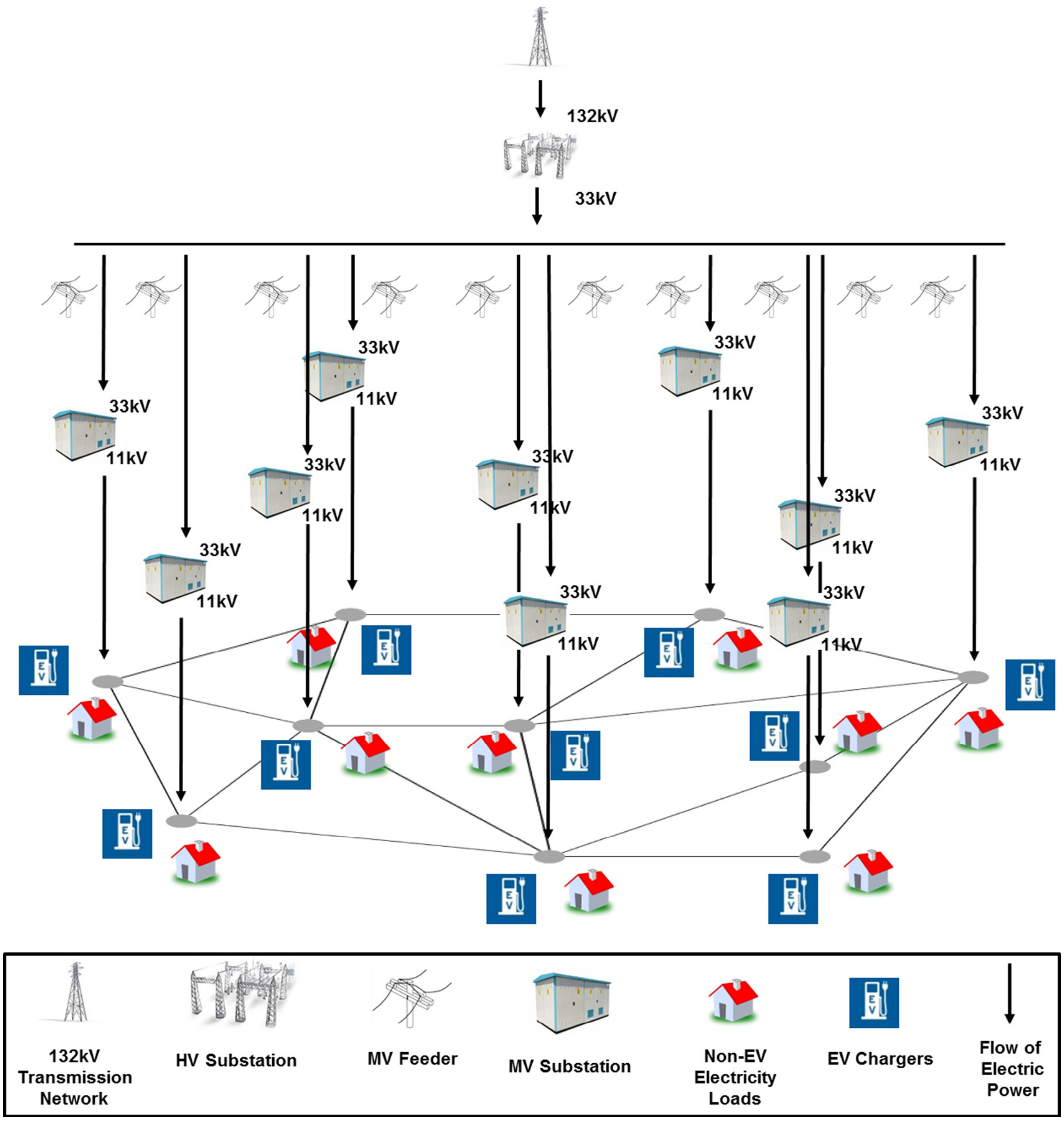


Figure 2.16: Similiar work in [12], 8 nodes network.

Chapter 3

Agents Layer

The social layer can also be defined as a *decision layer*. In fact, agents receive the "static"information from the environment (road network) and from it they decide the movements (Figure 3.1).

The output of the layer is the complete list of all trips, extracted from the *weekly routines*.

The objective of the chapter is to illustrate how the characteristics associated with the single agent contribute to the definition of its own week.

As explained in *Chapter 2*, each agent is distinguished in a proper and independent way. The choice of the characteristics that compose the computer object *"driver"* is an assumption made by the programmer. Assigning a particular property has an heavy impact on the goals that the agent will have. To avoid the mistake of giving parameters that are too 'ad hoc', each characteristic of the driver derives from a theoretical background designed to recreate realistic behavior as much as possible.

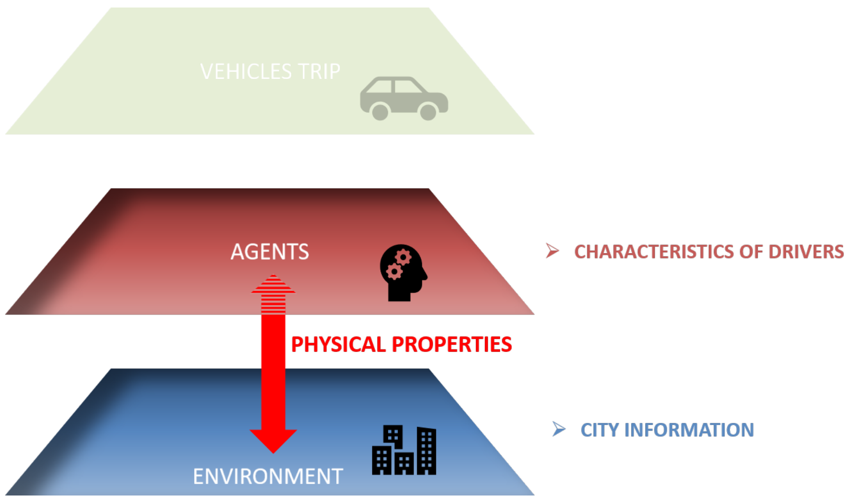


Figure 3.1: Exchange of information between the physical layer and the decision layer.

3.1 Description of the agents

Each agent is characterized by different parameters that recreate its personal characteristics. These characteristics play a fundamental role in the creation of the *weekly routine* of the driver, that is the objective of the analysis of this level. The actions that the agent must perform are identified by the place of execution. An agent can then find in its own routine:

- *HOME*, means that the agent is at home.
- *WORK*, means that the agent is at work.
- *ERRAND*, means that the agent is away from home for shopping.
- *LEISURE*, means that the agent is away from home to have fun.
- *OUT*, means that the agent is outside the simulated environment.
- *ILL*, means that the agent is ill.

The paragraph has the task of explaining how the activities are assigned to each agent and the decision path to assign the location in which they are carried out.

The characteristics that make it unique agent are manifold:

1. *NODE HOME* The agents, in the model, reside in the city nodes. The city nodes represent the neighborhoods supplied by one or more *MV/LV* substations.

   The home node identifies the city node in which the agent lives. The definition of this node is fixed as it is assumed that each driver has a single dwelling. The assignment of the home node is not random, but is obtained by extraction from the Cumulative Distribution Function (*CDF*) of residential powers. The nominal powers of each electrical node are in fact divided into:

   - *Residential power* - P_{res}
   - *Industrial power* - P_{ind}
   - *Commercial power* - P_{com}
   - *Tertiary power* - P_{ter}
   - *Agricultural power* - P_{agr}

   The residential power of a city node corresponds to the sum of the residential powers of the electrical nodes that supply it.

   The extraction of the home node takes place in two steps. From a uniform probability distribution we extract $r \in [0,1]$. The extracted number is the input for the extraction of the city node from the CDF of the P_{res}. Nodes with greater aggregated residential power will be more likely to be extracted. This assumption appears to be consistent as it is reasonable to think that a high residential power corresponds to a large number of homes and family units served.

2. *NODES WORK* There are two work nodes assigned to each agent in the model. The main place of work and the place of transfer.

   - The main working node is the principal place where an agent works.
   - The working away node is expected considering that some categories of workers move in more than one working place (in the same city) during the week.

   The two nodes can never coincide.

   The extraction, as done for the home node, takes place by cumulative with respect to the aggregated working powers. For aggregated working powers we mean the sum of industrial, commercial, tertiary and agricultural powers of the electric nodes included in the city one.

   The two-step extraction, shown in Figure 3.2 is maintained.

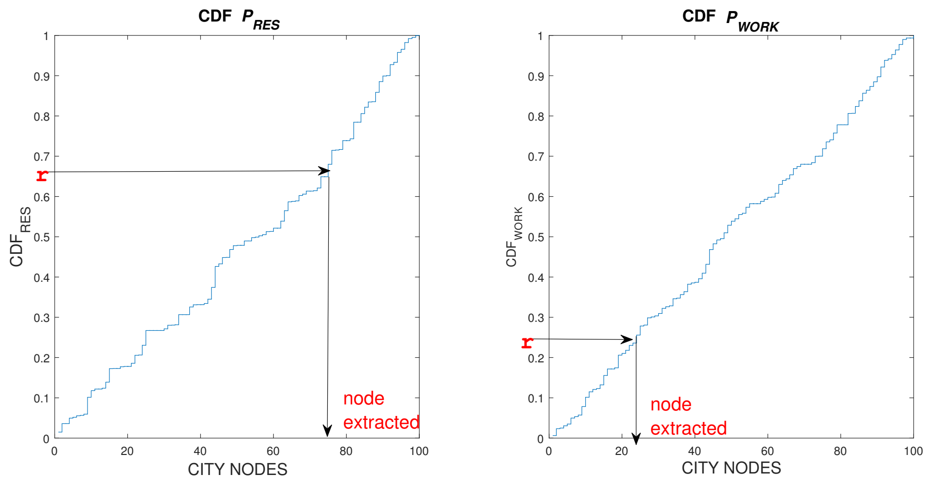


Figure 3.2: CDFs to assign the home and work nodes.

3. *SEDENTARY* The parameter indicates the tendency of an agent to perform "non-work actions"in the neighbors of the node in which the person corrisponding to the agents lives. The characteristic of the agent is represented by a curve that changes the cumulative errands and leisures for the estraction of the respective actions. Far nodes will be penalized; the agent will have little chance of going there even if they correspond to a great power (high attraction). In any case, the probability of extraction of these nodes is not zero. This process is summarized by Figure 3.3.

   The parameters extracted that will influence the *errands* and *leisures* actions are two:

   - *Threshold*, expressed in [km], indicates the minimum distance above which the agent moves with the car to perform the action. Since the purpose of the model is to highlight the movements in the car, actions cannot be taken in nodes geographically close to the home node. This parameter tries to replicate the "laziness"of the agents. A lazy agent can use the car even for small movements.

The extremes within which the threshold can be extracted are:

  – 0.6 [km] -> distance within which it is assumed that nobody takes the car.
  – 1.5 [km] -> hypothesised distance beyond which nobody goes on foot.

- τ, represents the time constant of the conditioning curve. It is assigned by remembering that the function tends to zero in 5τ. This parameter models the behavior of people who tend to carry out their activities around the places where they live.

  The extreme representations of the agents habits, within which the parameter is extracted are:

  – $\tau_{\text{min}} = number\ of\ nodes/5$ -> very sedentary agent (the last nodes have very low probability of being extracted).
  – $\tau_{\text{max}} = number\ of\ nodes$ -> not very sedentary agent. The distant nodes are penalized in a slight way.

4. *CDFs ERRAND - LEISURE* The nodes where agents go for non-working actions are not fixed. The destination is extracted trip by trip through the conditional extraction of the CDFs errands / leisures, ordered geographically. The cumulative functions are conditioned, as seen, by the sedentary parameter. This should simulate people's greater propensity to make commissions close to home, for example.

   The errands nodes are extracted according to commercial powers, the nodes leiusres those tertiary.

5. *FAMILY* The parameter family is a bit $\in [0,1]$ simply indicates if the person corresponding to the agent has family. In fact, it has been thought that the times and activities of a person are different if he lives alone or in a family nucleous. The assignment is of probabilistic type with $p = 50\%$.

6. *TYPE* This is perhaps the most important characterization. Depending on the node in which the driver works, the work sector (industrial, commercial, tertiary, agricultural) is extracted from the cumulative work node. Based on the Italian ISTAT 2017 [23] data, the type of employment is assigned, with different probabilities depending on the sector of work, between:

   - full time worker
   - part time worker
   - freelancer

   A share of agents can also result as a "random agents". They will be characterized by random trips to insert an additional stochasticity to the model.

   The percentages used to assign the type of work with respect to the type of use are shown in the Table 3.1.

Table 3.1: Assignment of the type of agent on the basis of Italian ISTAT data

	WORK FULL TIME	WORK PART TIME	FREELANCER	RANDOM
INDUSTRIAL WORK	0.9	0.5	0	0.5
COMMERCIAL WORK	0.65	0.2	0.1	0.5
TERTIARY WORK	0.7	0.15	0.1	0.5
AGRICULTURAL WORK	0.85	0.1	0	0.5

7. *ACCURATE* This parameter further differentiates the activities of an agent compared to those of another similar agent. In fact, each driver is described according to the ability to follow the schedules of their commitments. Each time the agent moves from one activity to another, the true starting time of the new action is calculated. The true time is calculated by adding or subtracting Δt, extracting from normal distribution with expected value of zero and variance thirty minutes (this means that 94.45 % of the extractions takes place in the range [0-30 minutes]). The extracted value indicates the "flexibility"of the agent to start a new activity. The ideal trip start time is therefore obtained by subtracting the estimated travel time (based on shortest path) at the start time of the activity. Also by extracting from normal distribution an eventual delay/advance of the agent with respect to the starting time is calculated. The temporal discretization is one minute. Figure 3.4 shows the logical path with which travel times are obtained.

8. *EV USER* The bit $\in$ [0,1] indicates whether the agent is a user of PEVs. The number of drivers using battery-powered vehicles is parameterized by the penetration value of PEVs compared to total agents.

9. *WEEKLY EVENTS* One bit $\in$ [0,1] indicates if the agent spends the week at home due to illness. The probability that the person is ill all week is 5 %. The corresponding assigned action is declared as *"ILL"*.

   One bit $\in$ [0,1] indicates whether the agent spends the week outside the city. In this case the corresponding activity is *"OUT"* for every hour of every day and this does not produce useful trips.

10. *DAILY EVENTS* Every weekday the possibility that the agent is out of town is extracted. If the agent is in the city, the work site is extracted, choosing the main office and the secondary office.

    Also for the weekend there is the possibility that the agent is outside the simulated space. As with the other *"OUT"* activities, its actions do not create simulated trips

3.2 Agent's routine

All the parameters seen so far have the purpose of personalizing the agents week as much as possible. The output of the *Agents layer* is the representation of the list of actions associated with each simulated agent.

The actions assigned to each agent are classified into three types:

- *fixed actions*
- *semi-aleatory actions*
- *aleatory actions*

The characterization of the *driver type* provides, according to the reference category, a *"standard routine"* (loaded from Excel). This table broadly replicates which are the *fixed actions* that an agent must perform during the week (for example work activities). The actions contained in them and the relative timetables have been chosen in a manner consistent with the most common types of contracts in Italy. Once the weekly reference routine has been assigned, other weekly/daily actions are assigned to the driver, according to the other parameters that describe him.

The actions called *semi-random* are used to customize the profile. They are described as a block of activity that the agent will have to perform during the week, but without knowing in what days will take place. A typical example is the agent with family who two days a week (extracted) will take the children to school before going to work.

In Excel are also described the possible *aleatory actions* that one person could perform according to its characteristics. These actions are called 'aleatory' because their realization is random according to a uniform extraction. An example of what has been described is found in Table 3.2.

Table 3.2: Aleatory actions for work full-time agent.

START	END	PROBABILITY	ACTION	ACRONYM
18	20	0.5	ERRANDS	NFWD
20	23	0.2	ERRANDS	NFWD
10	12	0.5	ERRANDS	NFWE
16	18	0.4	ERRANDS	NFWE
10	24	0.6	ERRANDS	NFWE
18	19	0.5	ERRANDS	WFWD
21	23	0.1	ERRANDS	WFWD
10	12	0.2	ERRANDS	WFWE
16	18	0.5	ERRANDS	WFWE
20	24	0.3	ERRANDS	WFWE

The acronym indicates when the proposed actions could be assigned, according to the legend of Table 3.3.

An example of characterization of an agent is shown in Figure 3.5.

Table 3.3: List of Acronym.

ACRONYM	
NFWD	No Family Working Days
NFWE	No Family Week End
NFWD	With Family Working Days
WFWE	With Family Week End

As explained previously, the characterization of an agent is essential for the creation of a model consistent with the study to be performed.

From this point of view, the possibilities of refining the social layer are many. However, for the level of detail to which the thesis aspires, the proposed characterization satisfies the needs of the model. In fact, it is found that the population is varied and the departure and arrival times of the trips are distributed in a rational way.

Figure 3.6 represents the journeys carried out by all the agents in a defined scenario. One can observe how qualitatively the agents' journeys follow those of a real city (Turin).

The model can certainly be refined by adding those movements in the "off-peak"time bands. Also as regards the characterization of the weekends, a more in-depth research on how people use cars, would certainly lead to a more accurate simulation.

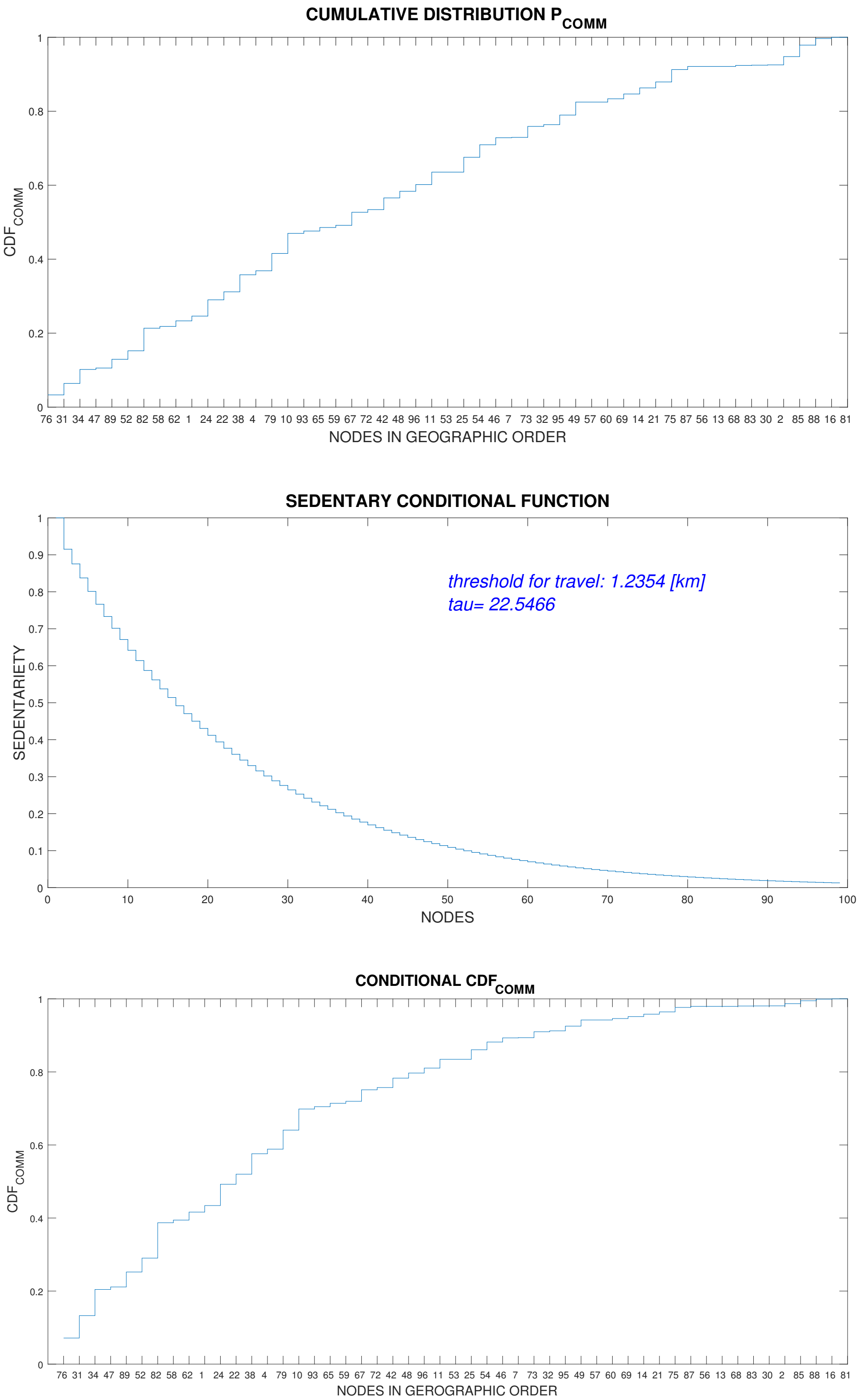


Figure 3.3: how to condition the CDF for the extraction.

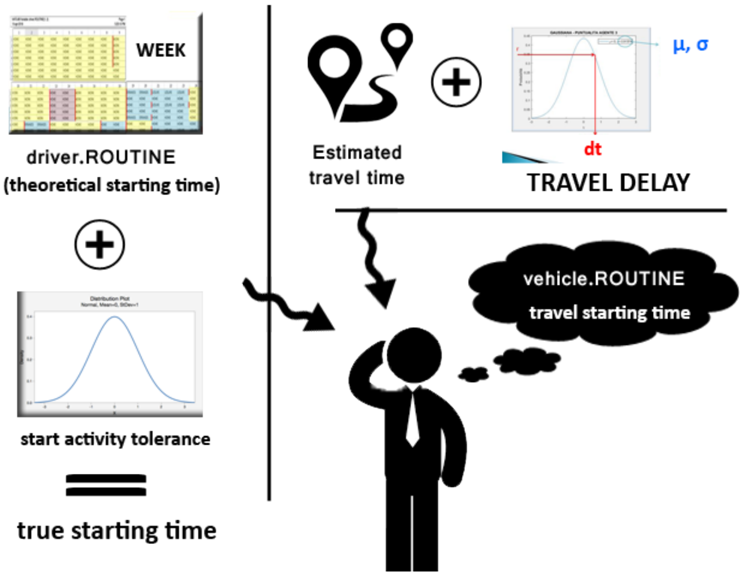
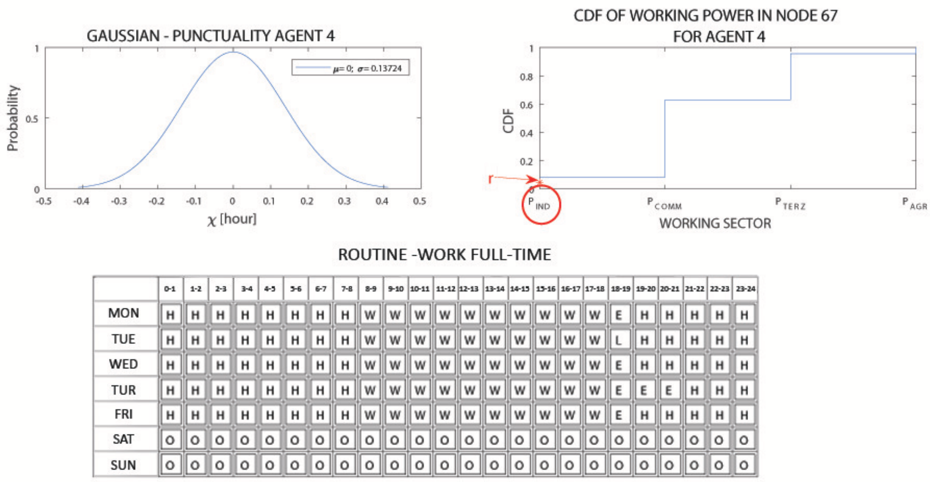


Figure 3.4: Timetable based on weekly activities.



	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
MON	H	H	H	H	H	H	H	H	W	W	W	W	W	W	W	W	W	W	E	H	H	H	H	H
TUE	H	H	H	H	H	H	H	H	W	W	W	W	W	W	W	W	W	W	L	H	H	H	H	H
WED	H	H	H	H	H	H	H	H	W	W	W	W	W	W	W	W	W	W	E	H	H	H	H	H
TUR	H	H	H	H	H	H	H	H	W	W	W	W	W	W	W	W	W	W	E	E	E	H	H	H
FRI	H	H	H	H	H	H	H	H	W	W	W	W	W	W	W	W	W	W	E	H	H	H	H	H
SAT	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
SUN	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Figure 3.5: Characterization of an agent.

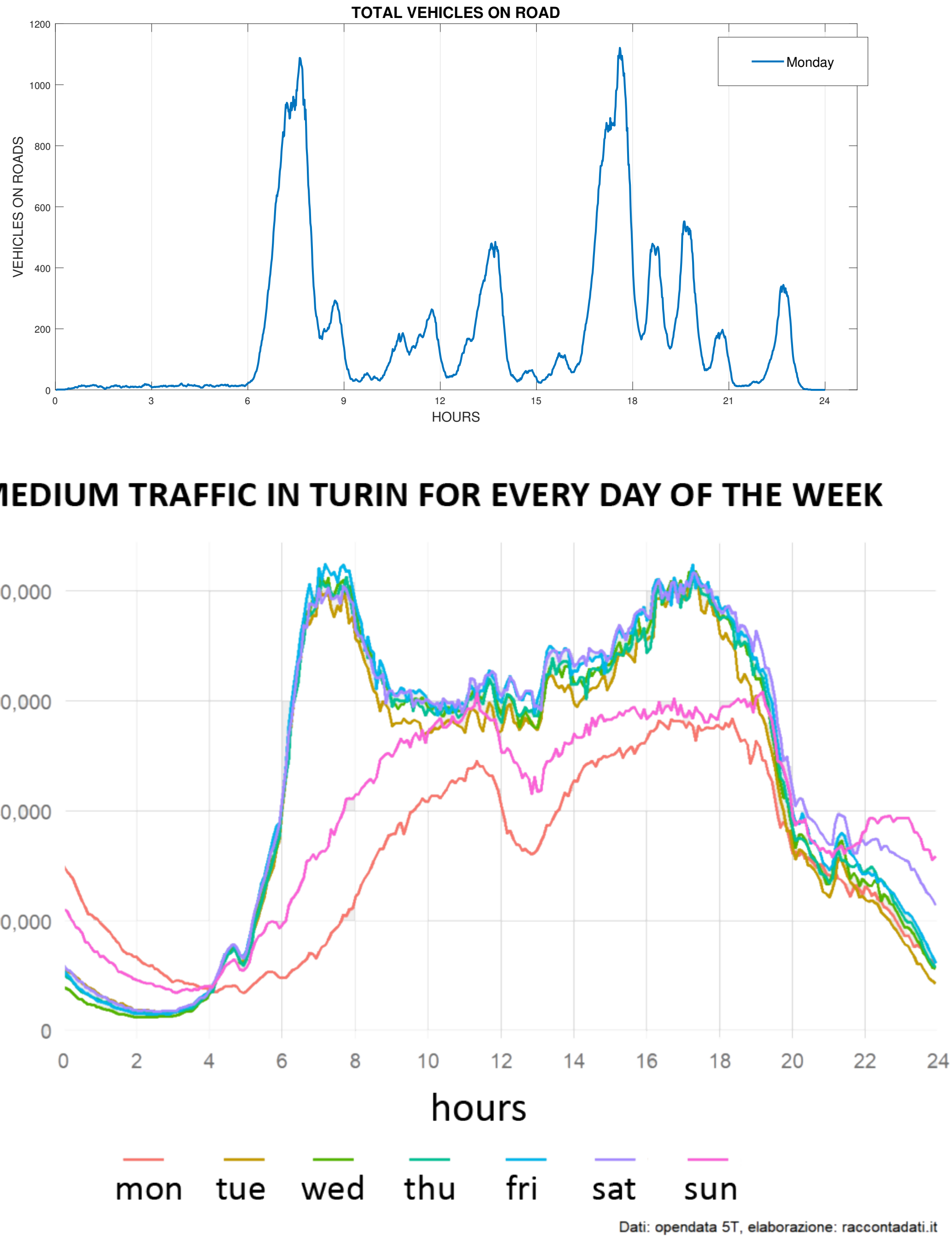


Figure 3.6: Traffic in the model and in Turin

Chapter 4

Environment Layer

This chapter describes how the layer in which agents move and interact was created. Agents in fact interact with each other but also with everything that the environment layer contains. Always keeping in mind the multilayer structure of the elaborate, the environment layer is exploded into three sub-levels:

- *ELECTRIC NETWORK*
- *CITY DISTRICT*
- *ROAD NETWORK*

All these environments are characterized by a *static* and a *dynamic* description.
Figure 4.1 shows in a synthetic way what will be described in the chapter.

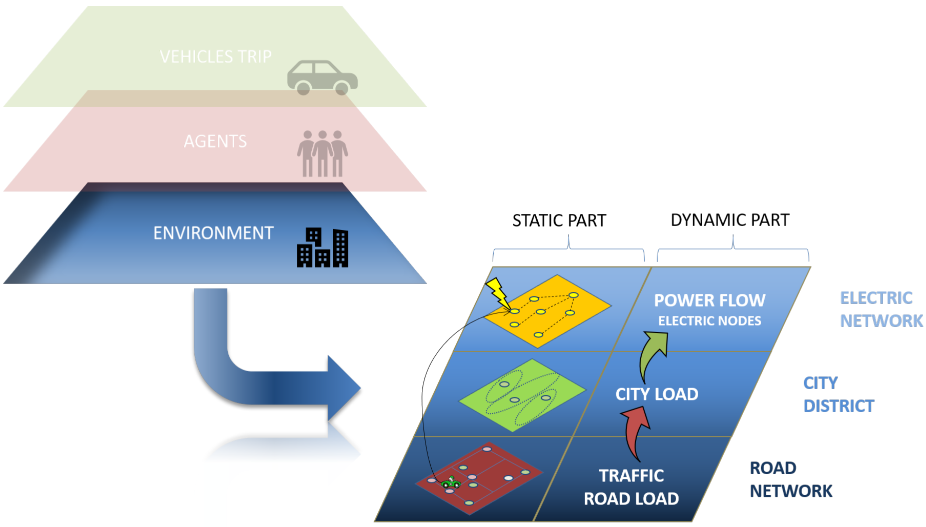


Figure 4.1: Environment layer exploded.

Later it is told in detail which structures and models have been used in the elaborate. The dualism of static and dynamic descriptions will be a feature present in every part.

4.1 Electric Layer

The first environment described is the electric one. *Chapter 2* describes the main characteristics of the electricity distribution system.

In short, its structure is characterized by being of a weakly meshed type, with radial operation. Each node is connected to the HV/MV electric substation through a unique and reconstructable path through the inverse matrix of the incidences Γ.

Regarding the study carried out, two distribution electrical networks were used. The two networks differ in structure and nodal loads in:

- *Semi-urban network*
- *Rural network*

Both networks reflect the theoretical descriptions and operate (with radial configuration) independently of each other. In reality, the two networks are connected to each other via the electricity transmission system (Figure 2.10). Due to the characteristics of the transmission system (meshed network, subject to voltage and frequency adjustments), it can be considered as ideal from the point of view of the electrical distribution system. This results in the independence of the so-called *slack* (HV/MV) nodes, each of which is not influenced by the other distribution system.

The static description of the two networks is shown in Figure 4.2.

In the proposed model, the structures of the two power grids are the input on which the entire description of the city is constructed.

The geographical arrangement of the two networks is typical of a real condition. The semi-urban distribution network provides what can be referred to as the city center, the rural network provides the peripheral users, too far from the HV/MV cabin of the semi-urban network.

The dynamics of the electric networks is provided by the calculation of the power flows. The method used is the one described in *Chapter 2*, which is the Backward-Forward Sweep (*BFS*). The iterative procedure allows to calculate every time:

- the voltage of each node
- the current absorbed by each node
- the current in each branch.

The information obtained allows quick verification of compliance with or breach of network operating constraints.

An example of the output of the calculation is given by Figure 4.3, where the currents of all branches of the semi-urban electric network are visualized in an established scenario.

In order to carry out the calculation of the distribution of the power flows, it is necessary to know the load applied every time. The loads are described with their apparent power ($P + jQ$ [MVA]).

The load profiles at the nodes were calculated on the knowledge of two elements:

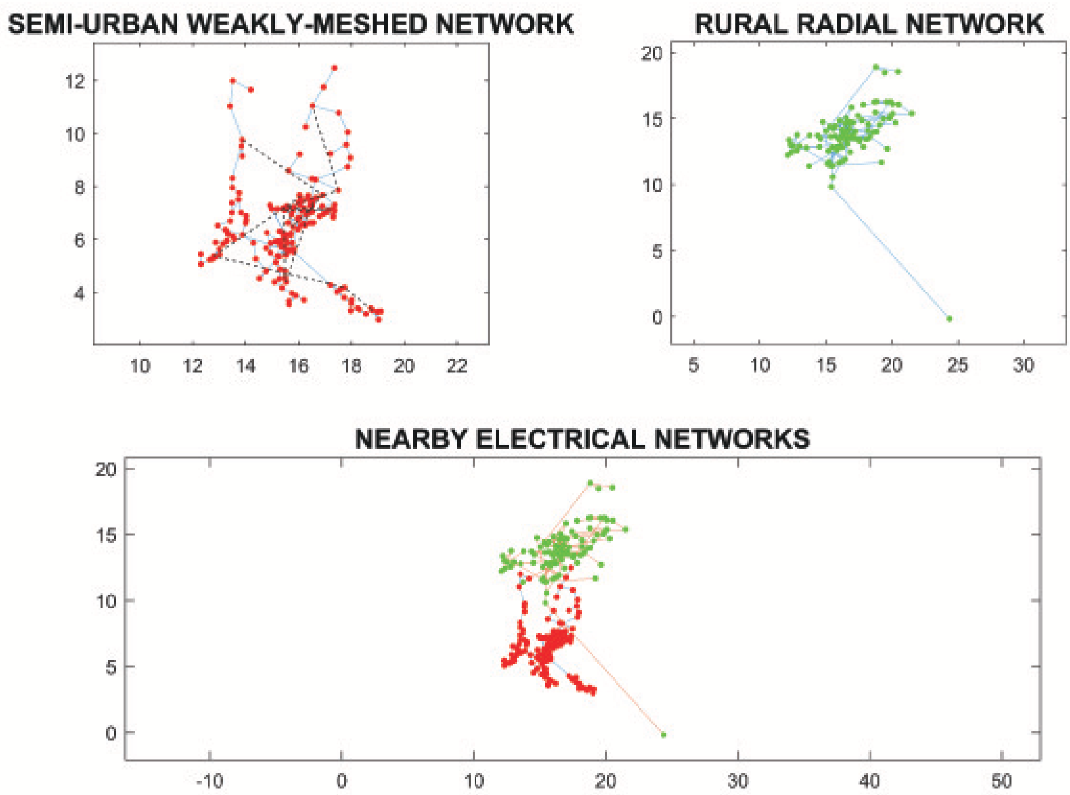


Figure 4.2: Electrical networks used for the study

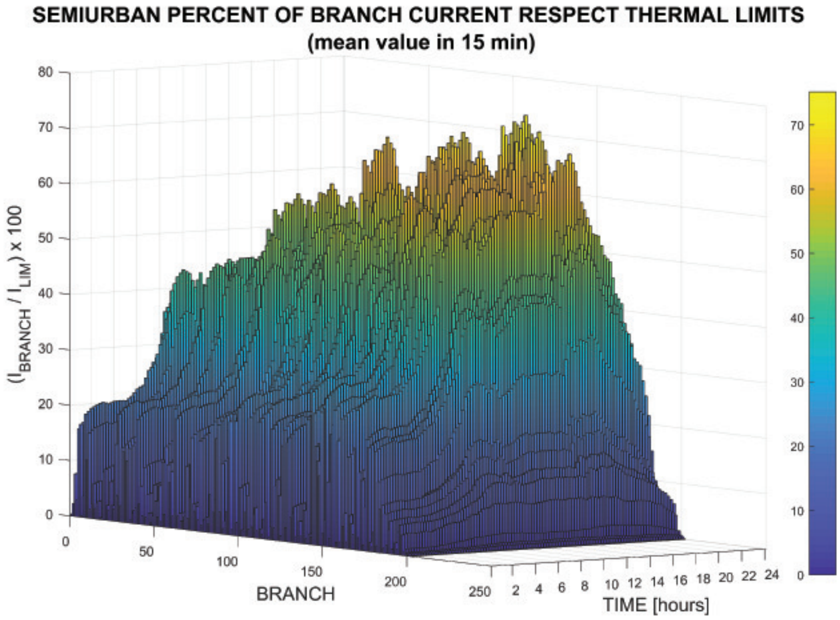


Figure 4.3: Current in the branches of the semi-urban network in the presence of PEVs. (1000 agents, 10% penetration of battery-powered drivers, charging station power 6 [kW])

- *Nominal powers* of each node (active [MW] and reactive [Mvar])
- A *"standard"load profile*, discretized at 15 minutes.

From the available information a customized profile has been extrapolated for each node of the networks, with a time resolution of 1 minute.
This has been carried out in two steps:

1. The standard profile has been extended from 96 to 1440 points (i.e., from a value every 15 minutes, it has been changed to 1 value every minute). Very simply it was decided to keep the aggregate load of a node constant. In this way the energy absorbed by the node in 15 minutes remains unchanged.
2. Given the nominal powers of each node (subdivided into residential, industrial, commercial, tertiary and agricultural) the standard profile has been construted. Mathematically this consists of multiplying the nominal power of the node under consideration $'k'$ for the load standard profile vector.

$$\begin{cases} \mathbf{p_{res}}^{(\mathbf{k})} = P_{\text{nom,res}}{}^{(\text{k})} \cdot \mathbf{p_{res,standard}} \\ \mathbf{p_{ind}}^{(\mathbf{k})} = P_{\text{ind,res}}{}^{(\text{k})} \cdot \mathbf{p_{ind,standard}} \\ \mathbf{p_{com}}^{(\mathbf{k})} = P_{\text{com,res}}{}^{(\text{k})} \cdot \mathbf{p_{com,standard}} \\ \mathbf{p_{ter}}^{(\mathbf{k})} = P_{\text{ter,res}}{}^{(\text{k})} \cdot \mathbf{p_{ter,standard}} \\ \mathbf{p_{agr}}^{(\mathbf{k})} = P_{\text{agr,res}}{}^{(\text{k})} \cdot \mathbf{p_{agr,standard}} \end{cases} \tag{4.1}$$

As for the nodes, also the electric branches in the model contain some information that allow the calculation of the voltage drops and losses on the branches during the calculation of the power flows.

The analytical report that links the value of the voltage in a node, with respect to the line impedance (Z_{B}), derives from the basic electrotechnics. In fact, it is calculated by summing the voltage drops (amplitude and phase) on each branch that connects the node under examination to the power supply slack node.
For node i, at iteration k:

$$V_{\text{i}}{}^{(\text{k})} = V_{\text{i}}{}^{(\text{k-1})} - \Gamma(i,:) \cdot Z_{\text{B}}{}^{(\text{i},:)} i_{\text{B}}{}^{(\text{k})} \tag{4.2}$$

where the voltage drop on a branch is calculated as:

$$\Delta\bar{V}_(B) = \bar{V}_1 - \bar{V}_2 = R_{\text{B}}\bar{i}_{\text{B}} + j \cdot X_{\text{B}}\bar{i}_{\text{B}} \tag{4.3}$$

As seen in *Chapter 2*, the criterion for stopping the iterative algorithm is the convergence of the voltage in each node. In the proposed model, when the calculated voltage (in a specific Δt) from one iteration to the other does not vary more than a threshold (fixed equal to $\epsilon = 10^{-4}$) the "photograph"of the network is considered known.

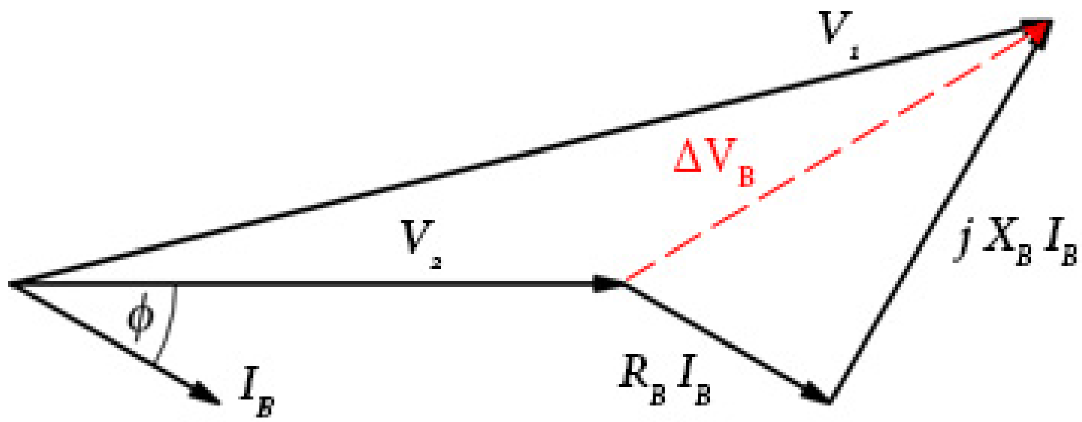


Figure 4.4: Voltage drop on branch.

Also the calculation of Joule losses goes through the knowledge of the impedance of each branch. The value of operational losses can be a goal to be minimized in a multi-objective function for the network operator (DSO).

Finally, each branch is characterized by its own thermal limit, obtained starting from the section and the type of insulation used (usually in Italy the MV lines are arranged in underground tunnels). The equation for obtaining the thermal limit of a conductor is obtained from the equilibrium between the thermal Joule power generated by the entire volume of the conductive material and the thermal power exchanged along the external surface of the insulating:

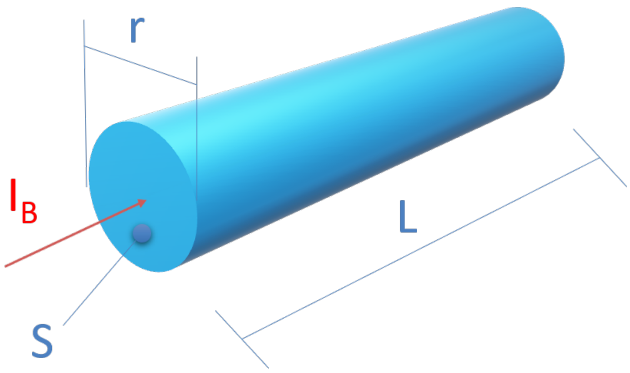


Figure 4.5: Electrical conductor.

$$P_{\mathrm{J}} = R_{\mathrm{B}} {I_{\mathrm{B}}}^2 \text{ (thermal power generated in the conductor)}$$
$$P_{\mathrm{S}} = \lambda(\Delta\Theta) 2\pi r L \text{ (thermal power exchanged on the surface)}$$

$$P_{\mathrm{J}} = P_{\mathrm{S}} \rightarrow I_{\mathrm{thermal}} = \sqrt{\tfrac{2\pi^2 r^3 \lambda(\Theta_{\mathrm{C}} - \Theta_{\mathrm{A}})}{\rho}}$$

where:
λ = thermal transmission coefficient
Θ_{C} = maximum temperature tolerated by the insulation
Θ_{a} = temperature of the environment
ρ = electrical resistivity of the conductor

The branches that make the network weakly meshed do not enter in the Γ matrix calculation, and are recognizable by *Status* equal to zero.

4.2 City Layer

The city layer has great conceptual value but from the dynamic point of view it is not very significant.

In fact, it represents the city districts, each of which is supplied by one or more MV/LV substation. City nodes represent attractions for agents. In fact, in its the protagonists of the model live, work, go to make shopping, etc.

The city nodes are obtained starting from the electrical nodes through a *k-means clustering* (see the *Background* chapter). This algorithm allows to aggregate a certain number of starting nodes in a fixed number of desired nodes. In the study, it was chosen to get 100 citizen nodes. The electrical nodes, the sum of the two distribution networks, are 304 (202 from the semi-urban network, 102 from the rural network).

The urban nodes, from the electrical point of view, are "equivalent electrical nodes". In fact they are described in the same way as the starting electric ones. The information contained in each node are:

- Number
- Active nominal power (divided into categories)
- Nominal reactive power (divided into categories)
- Geographical position (in Cartesian form)

Based on the characteristics of each city node (in particular the active nominal power), an agent has more or less probabilities of interaction. For example, a node with a very high commercial power is very attractive for an agent who has to do an activity such as shopping. These dynamics are described in the previous *Chapter 3*.

As mentioned, the dynamic description is not very significant because the studies carried out have the purpose of highlighting purely electrical properties. The implementation of citizen nodes, however, opens the possibility of carrying out sociological studies and, from the conceptual point of view, is an inevitable transition.

The following figure shows the result obtained, subjecting the joint electrical networks to clustering.

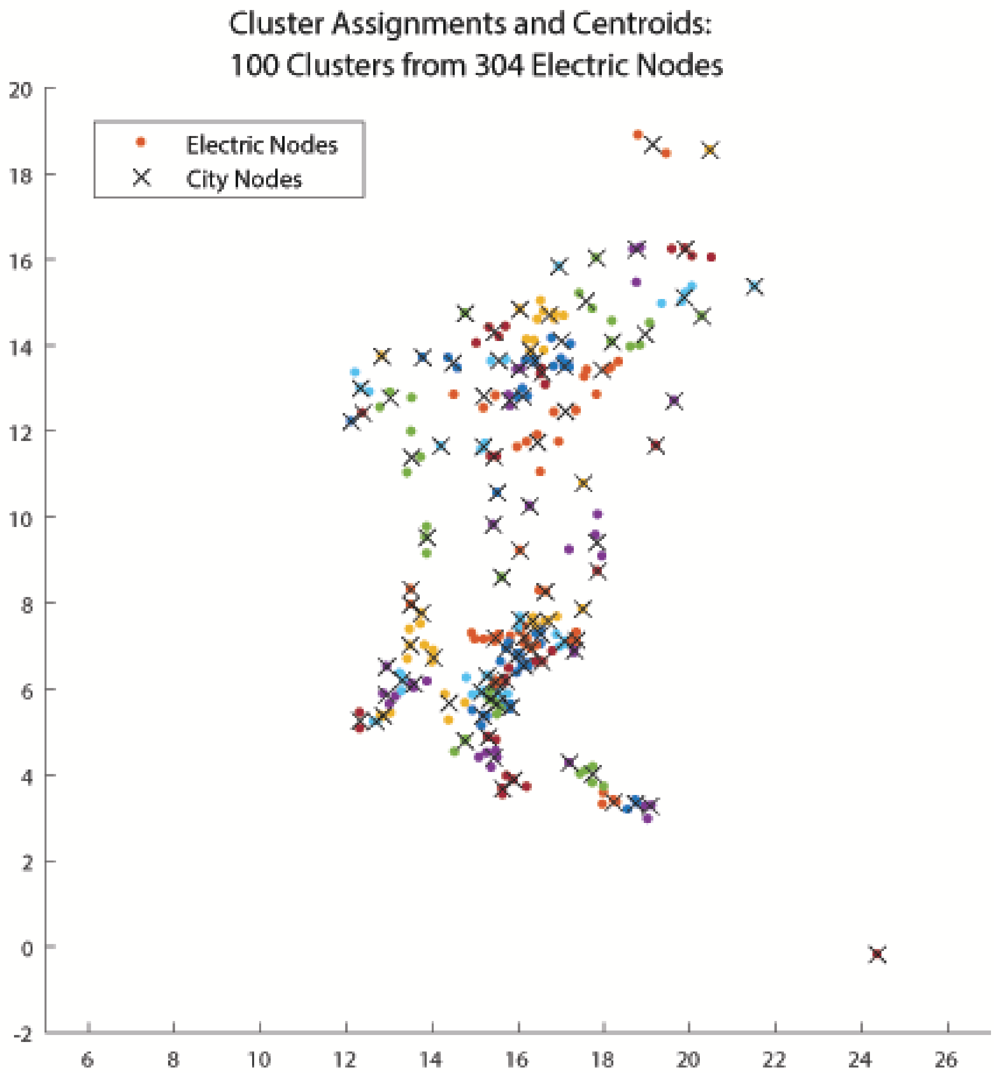


Figure 4.6: Result of k-means clustering

4.3 Road Layer

The sublayer that implements the road network has both static and dynamic value.

The static description of the road network is obtained starting from the city districts (clusters from the starting electrical nodes).

When there is the problem of having to study a road graph, the recommended approach is to use a real network. Road graphs are in fact available on various specialized platforms or are easily viewable by Google Maps. However, for the thesis, it was decided to create a fictitious road network from scratch, remaining consistent with the fact that even the electricity network used is not real but is a test network used by the reserchers into electrical engineering department of the Politecnico di Torino. In this way it was possible to highlight the link between the different levels of the model.

Taking inspiration from the work done by Basu and Sengupta [17], a quadratic graph was built around the neighborhoods of the city described in the previous paragraph. The algorithm created, called *"quadratic-tree algorithm"*, has as input the starting city nodes (with all the information that accompany them) and in output provides the branches and road nodes without duplicates. According to what has already been described in the corresponding part of *Chapter 2*, the road nodes represent the entry/emission points of the vehicles while the branches are the corresponding roads. The algorithm follows the flow-chart of Figure 4.7.

In practice, the total area of the city is divided into "zones", containing a number of urban nodes. The division is iterative and the stopping criterion is the maximum number of points that each zone can contain (to obtain the map used, this number has been set equal to four). The results of this algorithm are shown in Figure 4.8.

A summary of how the road map was obtained starting from the electrical networks is given in Figure 4.9.

The road network, as mentioned, is also relevant from the dynamic point of view. The interactions of the agents (on this level seen as *Vehicles*) are to be considered mutual and at the same time turned towards the environment. These interactions are summarized by the traffic. The traffic that is created on a road is in fact determined both by the contemporary number of agents that circulate there, and by the characteristics of the road itself. The traffic model used is presented in *Chapter 2* and includes three fundamental factors:

- average speed
- number of vehicles giving rise to slowdowns
- number of vehicles causing traffic congestion.

The model used is summarized in Figure 4.10.

Each road, generated by the *quadratic-tree algorithm*, is characterized by these three values, depending on the type of road.

There are four types represented:

- *Backbone*, entered manually in the program, represents the highway that crosses the city in lenght.

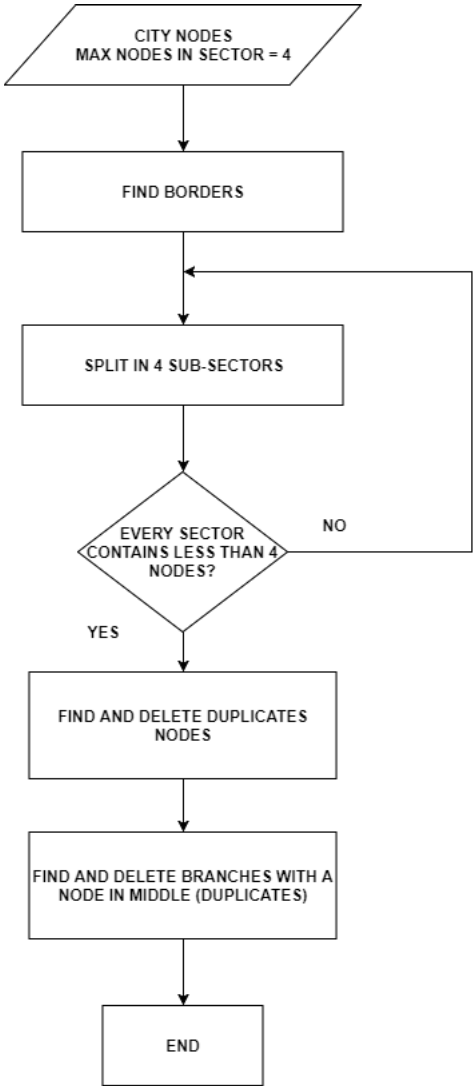


Figure 4.7: The quadratic-tree algorithm

- *Urban Road*, this category includes the short stretches of road in the heart of the city.
- *Semi-urban road*, to this category belong the extra-urban roads, characterized by longer lenghts and higher speed limits.
- *Rural road*, this category represents the most outlying streets, with limited width and difficult to travel in the presence of traffic.

The assignment of one category over another is made according to the number of subdivisions to which the sector has been submitted. This is easily verifiable by the name of the sector, as seen in Figure 4.8. The values assigned to the four categories are not fixed but are extracted from a normal distribution with mean value and variance (σ^2)indicated in Table 4.1. The parameters used are described in *Chapter 2*.

Table 4.1: Road type modelling.

ROAD TYPE	U_F	K_C	K_J	3σ
BACKBONE	25	8	20	1
URBAN ROAD	10	4	10	2
SEMI-URBAN ROAD	20	6	12	2
RURAL ROAD	15	3	15	5

For a correct functioning of the program, in particular the search for the best path through *shortest-path algorithm* (see *Chapter 3*) it is essential to eliminate the nodes and the duplicated branches, or those nodess/branches belonging to two or more sectors neighbors.

Figure 4.11 shows finally the road graph where the speed without traffic of each road section is graphically indicated. From this it is possible to visualize the backbone that crosses the city.

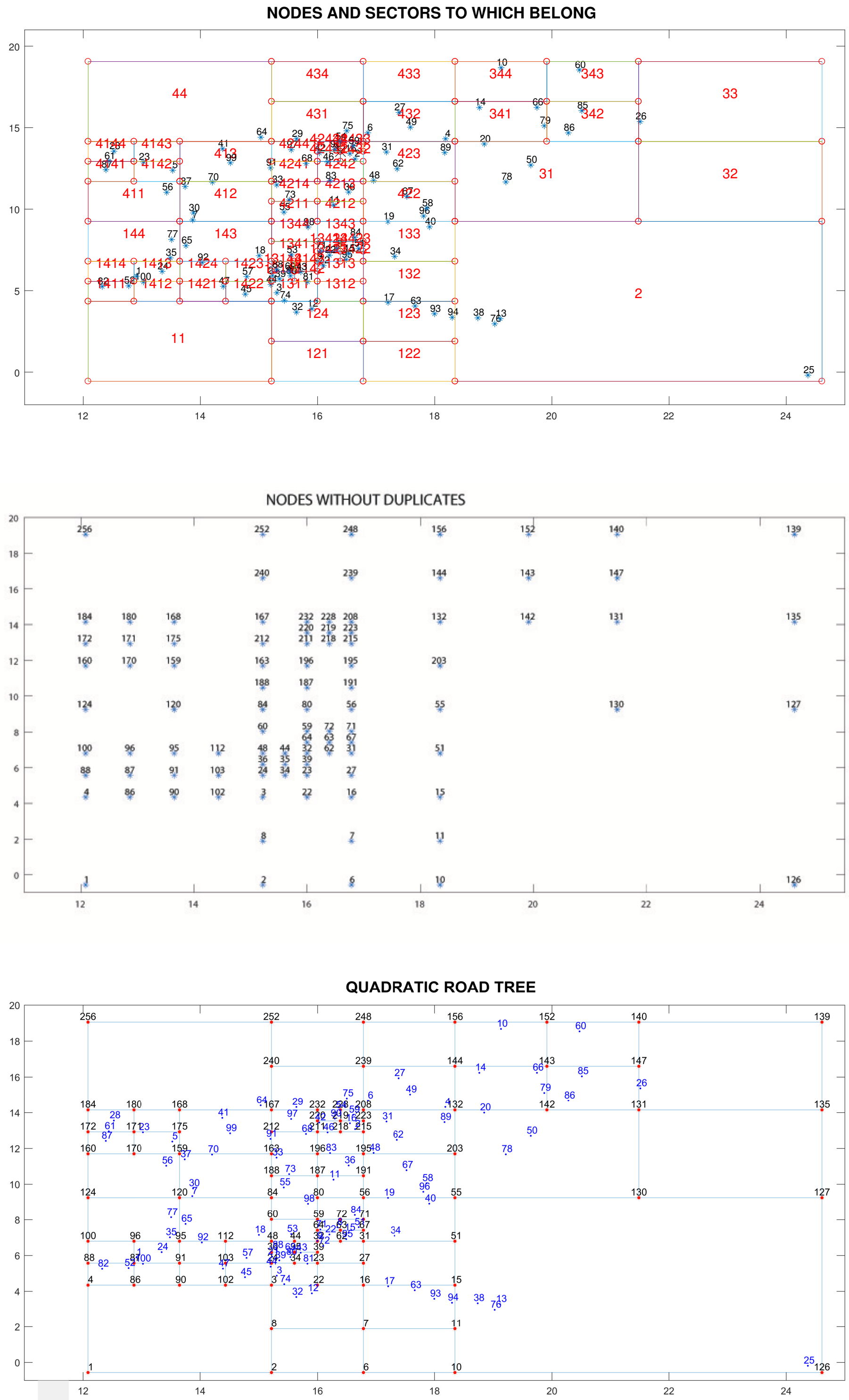


Figure 4.8: Results of the algorithm.

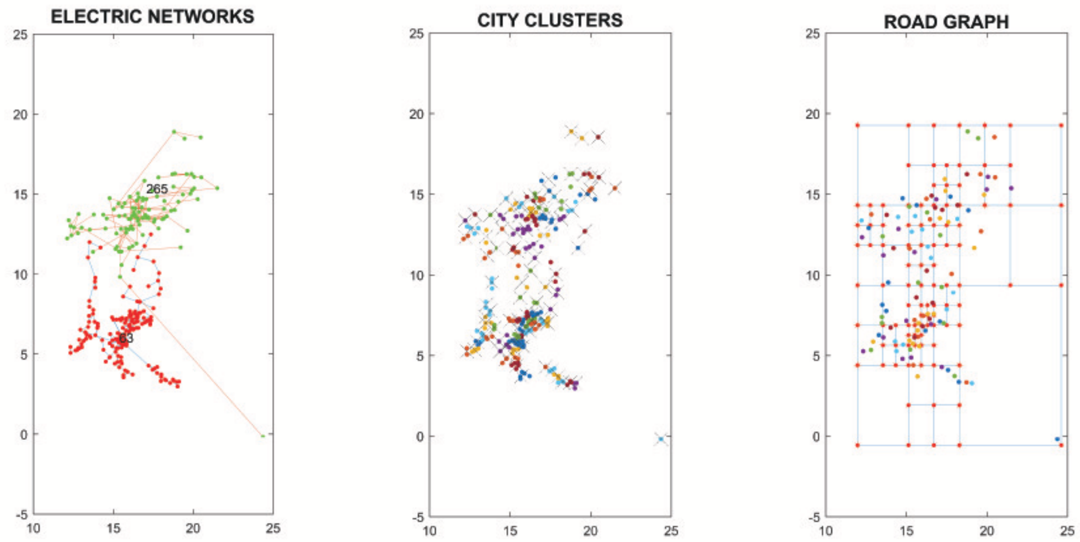


Figure 4.9: From electric network to road graph

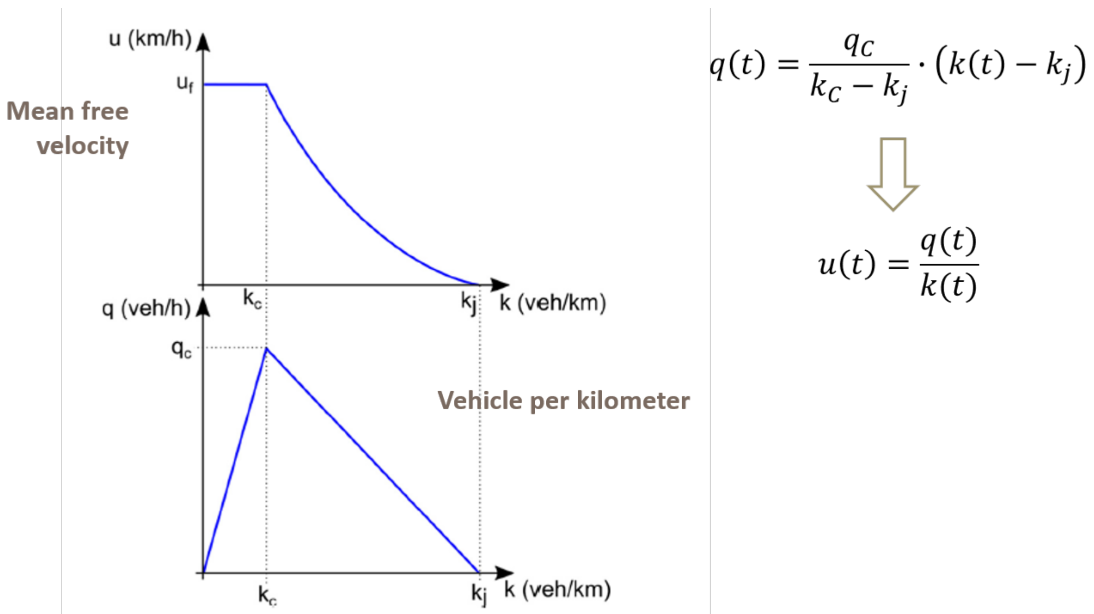


Figure 4.10: Maerivoet and De Moor traffic model

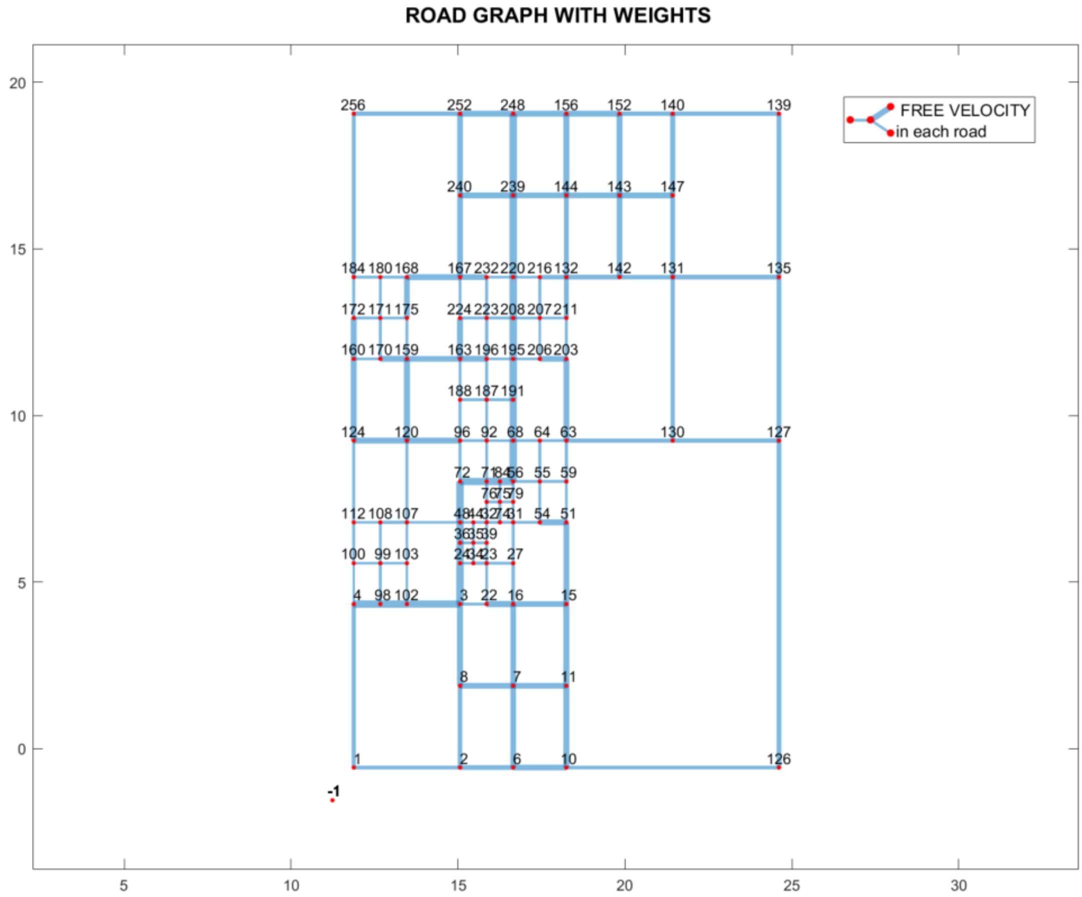


Figure 4.11: Road graph with speed limits.

Chapter 5

Case study implementation

This chapter explains in detail the procedure followed to implement the tool presented in the previous chapters.

The goal is to realize the thesis layer structure in an informatic tool (IT) environment. The software chosen and used for our studies is Matlab, exploited as a code. The use of a medium-level programming tool, rather than using programs already arranged, for example, to use agent structures (e.g., MatSim, Sumo, etc.), has made it possible to customize the information exchanged between the various objects of the program. It should not be overlooked that creating such software enabled the programmer to understand more in depth the potential of the algorithms used. The philosophy of the writer is that trying to achieve something from scratch certainly leaves more knowledge than using interfaces already present on the market, ignoring the complexities present within them.

5.1 A vision on the layout of the thesis

Considering the thesis structure, already proposed in the various previous chapters, it is evident how each level can be seen as an independent object that communicates with others. This optic allows to transfer the toric knowledge of each layer into IT objects. Each object is created as described in the previous chapters and is characterized by having both input and output. The multi-layer structure of the thesis is revived, trying to highlight how information crosses each conceptual level and then goes back as feedback (Figure 5.1).

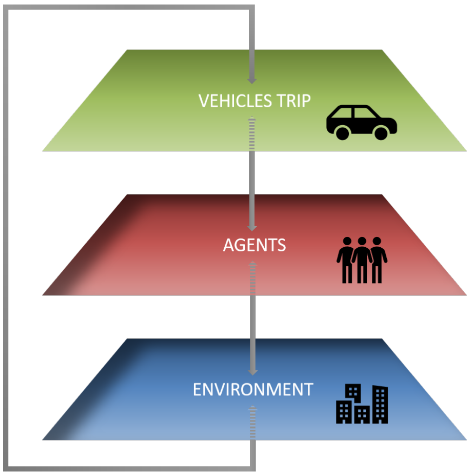


Figure 5.1: Communication between layers.

As seen, thanks to the description given, the creation of every informatic objects is independent. The programmer has the task of studying the characteristics of each level to give a correct description and to replicate mutual interactions.

To do this the approach used is very schematic. Figure 5.2 represents the conceptual map followed to proceed in the correct direction.

The blocks displayed represent the computer objects created:

1. *DATABASE OF PEOPLE TYPE:* represents the creation of macro-categories of people in which an agent can fall back. For each category different actions are assigned, different by type and time. the result is a database of possible characteristics that an agent can take.

2. *DRIVERS CREATION*: each agent (the number is parametrized) is created, assigning some general characteristics (e.g., if he has a family) and some more specific (e.g., where he lives), extracting in the database created above. These characterizations make each agent recognizable and different from all others. At this level, agents are called *Drivers*, as they represent people who use cars to make travel.

3. *DRIVER'S SCENARIO CREATION:* the driver's scenario is summarized by the weekly routine associated to it. The procedure for obtaining this description is not repeated here as it is explained in detail in the chapter *Social Layer Implementation.*

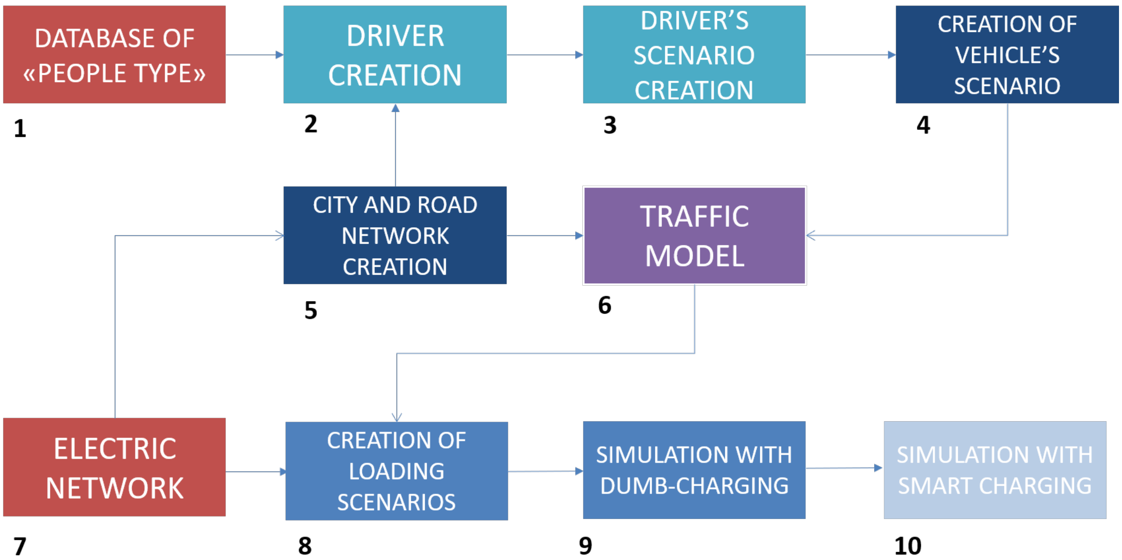


Figure 5.2: Framework of the thesis.

At the end of the procedure each agent knows the start of activities and start times of the trips.

4. *CREATION OF THE VEHICLE'S SCENARIO:* the scenario used is simplified, in fact the scenarios of the vehicles coincide with those of the drivers. This means that the journeys made are not influenced by external factors but only by the decision of the agent to move from one point to another, according to the choice of the fastest routes. In order to improve the proposed model, it is advisable to use the scenarios of aware users and unaware users proposed by Maramas [12]. In this case the "live"traffic information would influence the choices of driving agents (*Vehicles*) which would thus distinguish themselves from the *Drivers* agents. The scenario used considers the PEVs vehicles as part of a "car-sharing"service. In fact, an agent who has to make the trip has the possibility to choose between the different PEVs that may be present in the node. The choice, in the proposed model, always falls on the vehicle with the highest available SoC. The car-sharing scenario justifies in part the use of only one vehicle model with regard to consumption (reference vehicle = Nissan Leaf) 5.9.

5. *CREATION OF THE CITIZEN AND ROAD NETWORK:* the city network is created, according to what is described in *Chapter 4*, from the starting electric networks. The urban nodes influence the creation of the drivers, they are an input of the block (2). The static definition of the road network is also described in *Chapter 4* and represents the map in which the *Vehicles* agents move.

6. *TRAFFIC MODEL:* the computer block has as input the vehicle travel table and the knowledge of the road network. The output of the object is the electrical load generated by the PEVs vehicles stationed in the charging stations.

7. *ELECTRIC DEPARTURE NETWORKS:* in the proposed model there are two electrical networks: the semi-urban distribution system and the rural one. The two networks are described in *Chapter 4* and are the "raw"data on which the whole model is based. From the information output from this block it is possible to create the environment in which the agents live and carry out the final electrical studies.

8. *CREATION OF LOADING SCENARIOS:* this block is part of the electric strand. According to what has already been described, a temporal load profile is assigned to each node, to which is added the load imposed by electric vehicles that require charging.

9. *SIMULATION WITH DUMB-CHARGING:* represents the last operation performed in the model. After having recreated a satisfactory scenario (that is realistic and at the same time that allows to evaluate an effective impact of vehicles on the network), the "dumb charging"strategy applies to electric vehicles stationing at the nodes. The assumption made is that in each node it is possible to recharge the vehicle, without limitations of charging stations or maximum power absorbable at the node. A 'dumb charging' scenario is certainly the one with the greatest impact as the vehicles, just

parked, requiring the maximum power available from the charging socket to bring the SoC level up to 100% as fast as possible.

10. *SIMULATION WITH SMART CHARGING:* once you have defined the most interesting scenario in which to launch the program, it would be very interesting to carry out comparative studies to evaluate different strategies. The possible strategies are endless; you can think of reloading the vehicles when the SoC is included in a defined band (e.g., 20 % to 80 %), or to use the energy stored by the other vehicles to improve the absorption profiles V2G), etc . In any case, evaluating the decision-making impact of a centralized figure (e.g., the car-sharing service manager) is the next step to be taken.

5.2 Flow chart software

In this section we enter into the merits of the proposed software. The general structure is presented and the main functions created are shown.

As indicated in the previous paragraph, the computer objects described are well defined in structure and interactions. These objects are inserted in an *agent-based model*, characterized by a structure described in *Chapter 2*. The proposed structures are compatible thanks to the modularity with which the thesis was designed. Each block of the scheme proposed in Figure 5.2 is replaceable with another equivalent. This would simply result in a change of sceneries, the software structure would remain unchanged.

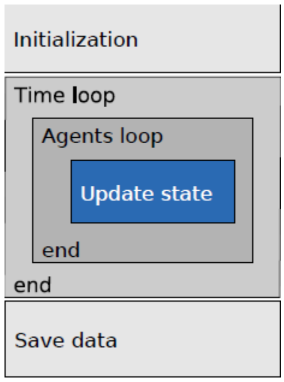


Figure 5.3: Agent-based software structure.

Examining the typical structure of an agent model of Figure 5.3, nested sections can be seen inside. The most significant are:

- *INITIALIZATION:* variables and agents are initialized in this block. The variables represent the randomness of the description of the environment. Agents are initialized as seen in *Chapter 3*.

- *TIME LOOP:* this block has not been detailed yet. It represents the temporal evolution of the initialized variables. The time loop scans the time progression of the model, time advancement that regulates the evolution of the overall system.

- *AGENTS LOOP:* within the temporal loop, each agent evolves and interacts with other agents and the environment. The agent cycle is essential to verify and possibly compute these evolutions.

- *UPDATE STATE:* when examining agent by agent within the *Agents Loop*, all of its dynamic characteristics are evaluated (e.g., its current position). Based on the available information, each internal state of the agent has the possibility to evolve.

- *SAVE DATA:* the last process, at the end of the computations, is the saving of the results. As explained in *Chapter 1*, agent models do not provide quantitatively perfect results. Their use allows the possibility of observing and making considerations on complex systems. Without these models, it would not be possible to imagine the evolution of such systems, too broad for human imagination. The results must therefore be consistent with what has been said. They must be qualitatively well described and consistent with the initial assumptions.

The organization of the software created is illustrated in Figure 5.4. Notice how the reference frame of sight is well recognizable.

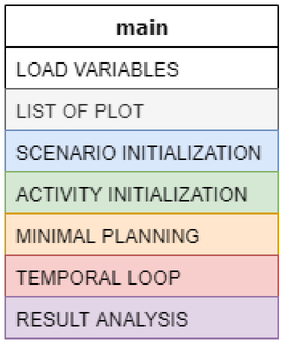


Figure 5.4: Organization of the software.

The main sections is equal to the reference structure; each step has been programmed from zero. For every function created there would have to be many things to say; we try to present at least the main structures. The main file is called *"main"*. It contains the sequence of execution of the various parts of the code, reordered as shown in Figure 5.4. Remember that the software has been created in Matlab language. The code is compiled sequentially.

LOAD VARIABLES The variables loaded by Excel are multiple and loaded in different moments. At the start of the simulation the fundamental parameters are read. They specifically correspond to:

- TEMPORAL PARAMETERS
  - Number of simulated weeks
  - Number of simulated days
  - Desired time discretization
- AGENTS PARAMETERS
  - Number of simulated agents
  - Percentage of agents using PEVs car sharing
- ENVIRONMENTAL PARAMETERS
  - Electricity network used
  - Number of desired 'city nodes' (city neighborhoods)
  - Road network used
  - Number of PEVs in each node at the beginning of the simulation
  - Power charging column

The parameters mentioned here are unchanged throughout the simulation.

LIST OF PLOT In this section the folder in which the results will be saved is created and, through a [0,1] bit, the plots to display at the end of the simulation are activated. At the end of the simulation, the screen printed plots are automatically saved in the created directory. The code used to create the new directory is the following:

```
%% ************* CREATE A NEW FOLDER IN CURRENT DIRECTORY *****************
%directory for saving workspace
folder=['RESULTS\N_DRIVERS-' int2str(par.N_DRIVERS),'#MAP-big','#%EV_DRIVER-' int2str(par.perc_EV), '#ROAD-' char(par.road_type),'#Pcolonnina-' int2str(par.P_station) '\'];
A = exist(folder);
if(A==7)
   'folder already exist'
   folder=[folder 'NEW''\'];
end
[status, msg, msgID] = mkdir(folder);
```

Figure 5.5: Create new directory in Matlab.

In the case of an existing directory (e.g, a simulation is repeated), the previous results are not deleted but a new folder is created inside, containing the new outputs.

SCENARIO INITIALIZATION In this function, the distribution systems under test are loaded and the temporary load scenarios are created. Starting from the electricity grid (or from nearby electricity grids), the tool proceeds, according to what has already been described, to the creation of the urban nodes first and then the road graph. It is important that in this path the correlation *road-citizen-electric* nodes is not lost. A vehicle being recharged in a road junction is a load for the corresponding electrical node. Figure 5.6 summarizes the link between the different parts content in the *Environmental layer*.

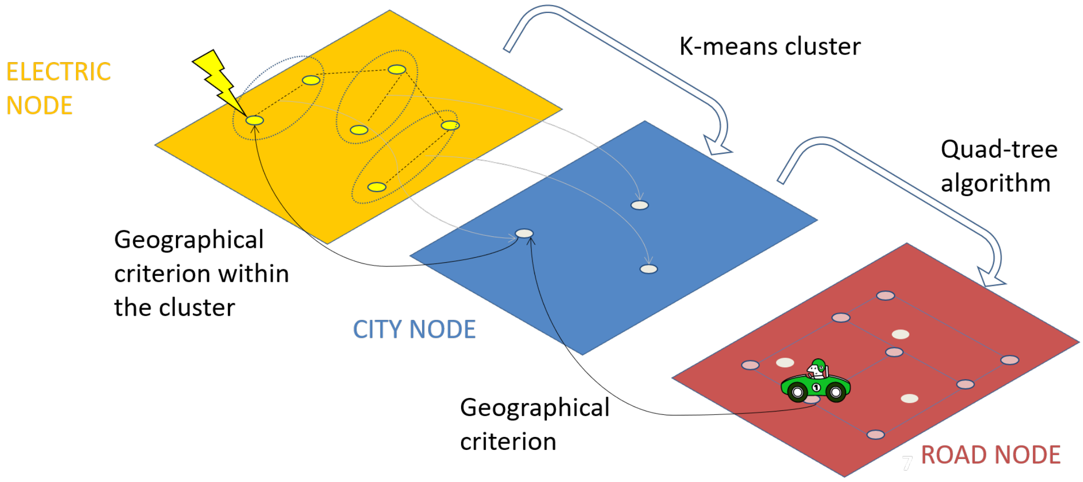


Figure 5.6: Inside of Environment layer.

ACTIVITY INITIALIZATION This function includes the creation of agents, according to what has already been extensively described above. Depending on the environment created, agents take certain characteristics and fill their weekly tables with actions. From the weekly routines all journeys are read according to the principle that a trip is required when one moves from an action to another different one, in the activity table (other than *"ILL"* or *"OUT"*). The structure *DRIVER TRIP* is thus obtained. An example of this structure is shown in the Figure 5.7.

Fields	FROM	TO	NODE_START	NODE_ARRIVE	NODE_ROAD_START	NODE_ROAD_ARRIVE	PATH	START_ACTIVITY	FLEXIBILITY	ESTIMATE_TRIP_TIME	DELAY	START	WEEK	DAY	EV_USE
1	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	8	0.0034	0.5459	0.0161	7.4736	1	1	0
2	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	12	-0.0036	0.5459	-0.0104	11.4400	1	1	0
3	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	14	0.0358	0.5459	0.0244	13.5143	1	1	0
4	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	18	0.0205	0.5459	0.0192	17.4938	1	1	0
5	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	8	-0.0171	0.5459	-0.0452	7.3918	1	3	0
6	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	12	-0.0674	0.5459	0.0619	11.4486	1	3	0
7	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	14	0.0080	0.5459	-0.0091	13.4530	1	3	0
8	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	18	0.0620	0.5459	0.0102	17.5263	1	3	0
9	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	8	0.0373	0.5459	-0.0351	7.4563	1	4	0
10	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	12	0.0051	0.5459	0.0043	11.4635	1	4	0
11	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	14	0.0064	0.5459	0.0258	13.4863	1	4	0
12	WORK'	'ERRANDS'	39	12	31	22	[31 27 16 22]	18	0.0208	0.2991	0.0876	17.8094	1	4	0
13	ERRANDS'	'HOME'	12	7	22	99	[22 3 102 103 99]	19	-8.5441e-05	0.3830	-0.0086	18.6083	1	4	0
14	HOME'	'LEISURE'	7	82	99	107	[99 103 107]	21	-0.0409	0.2023	0.0656	20.8224	1	4	0
15	LEISURE'	'HOME'	82	7	107	99	[107 103 99]	23	0.0114	0.2023	-0.0273	22.7818	1	4	0
16	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	8	0.0401	0.5459	-0.0423	7.4520	1	5	0
17	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	12	0.0253	0.5459	-0.0070	11.4724	1	5	0
18	HOME'	'WORK'	7	39	99	31	[99 103 107 36 32 74 31]	14	0.0404	0.5459	-0.0525	13.4420	1	5	0
19	WORK'	'HOME'	39	7	31	99	[31 74 32 36 107 103 99]	18	-0.0397	0.5459	0.0590	17.4734	1	5	0
20															
21															
22															

Figure 5.7: Example of Driver's Trips.

The travel list contains the information that the *DRIVER* agent has at the start of the journey. In fact, it is observed that the arrival time, or the time spent on the road, can not be known first in a simulation in which there are al lot of interactions. The only estimate that a driver can make is linked to the travel forecast in the absence of traffic, a condition to which the choice of the route taken is linked. From *DRIVER TRIP* we switch to *VEHICLE TRIP*, or to the list of travels of *Vehicles* agents moving in the road network. In the proposed model the two agents coincide but it is possible to divide them in this level, for example with traffic signals that change the trip to less busy roads.

MINIMUM PLANNING Keeping in mind that a car sharing scenario is proposed, it is unrealistic to have a large number of vehicles on each map in each node. A planning procedure is therefore created to minimize the number of circulating PEVs. In this way, an agent who wants to make an electric trip will not always have many cars to choose from, and the vehicles on the grid will have higher overall consumption. The planning procedure aims to give each node the least number of PEVs to guarantee all journeys. Otherwise the simulation would go into "fail"state and would be interrupted. There are numerous possibilities of realization. The choice made is to initially assign zero PEVs to each node and to simulate the week with a simplified time cycle. Whenever an electric trip is requested in a node, if there are no PEVs, one is created from scratch and will be assigned to the node under examination at the beginning of the actual simulation. The structure containing the results of the planning is called *"Num EV def"*. The results, in a defined scenario, are shown in Figure 5.8.

TEMPORAL LOOP The temporal loop is the computer object that simulates the time course of the simulation. It is undoubtedly the most complex and articulated function present in the program. In it we can recognize some fundamental structures:

- *TFO*, the *"Traffic Flow Object"* structure contains the list of journeys in progress in the time window $[t, t + \Delta t)$. The structure is obtained by reading the *VEHICLE TRIP* and contains the same information plus the calculation of the

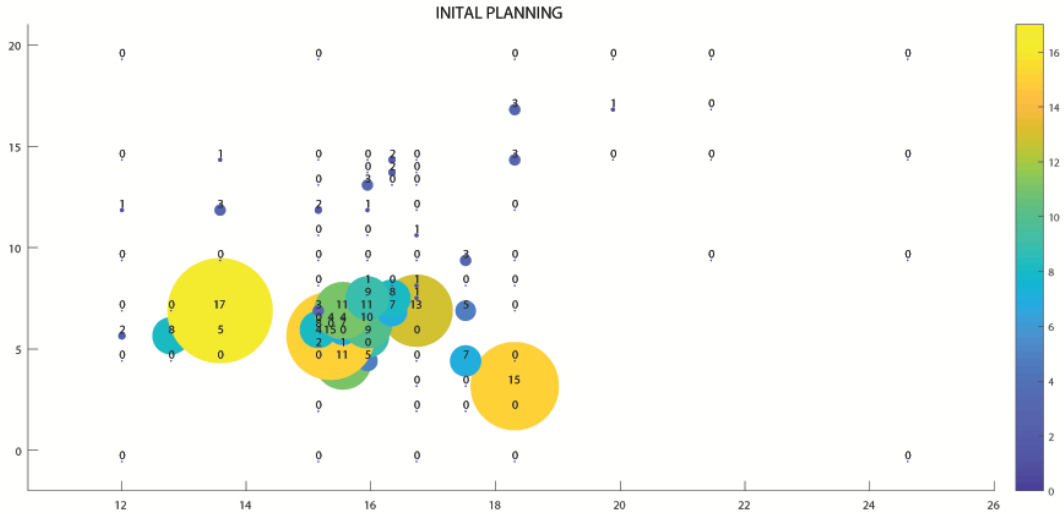


Figure 5.8: Effect of planning. (5000 drivers, 10% of PEVs user)

consumption of the PEVs.

- *P STATE*, the *"Parking State"* contains all the information of the simulated PEVs. Each electric vehicle is in fact characterized by a name, a position and a state of charge (SoC) level, calculated from the consumption and from the energy that can be stored by the battery. This information is summarized in Figure 5.9.

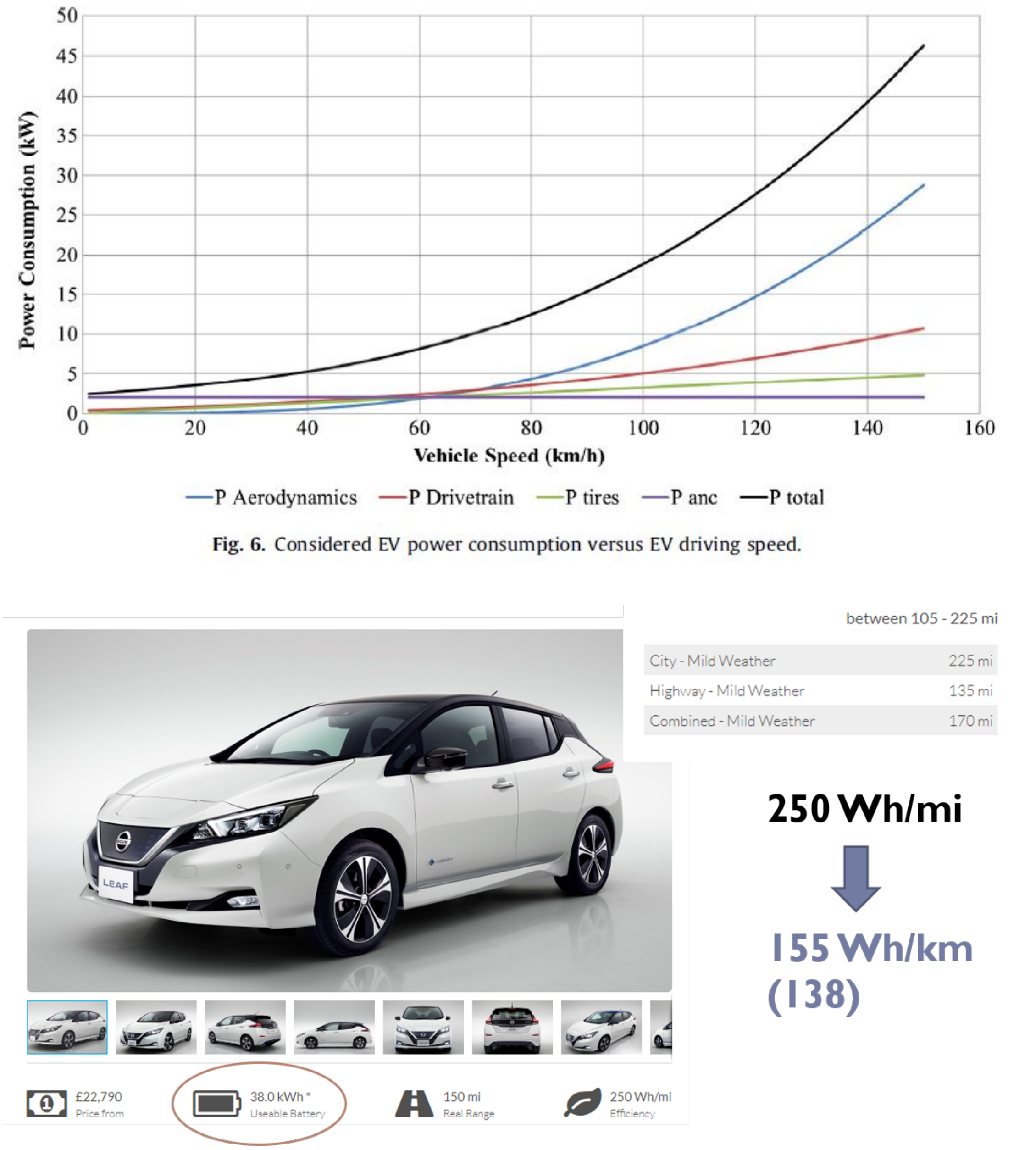


Figure 5.9: Vehicle's model used.

- *TFO Road*, is a variant of the *TFO*. The hourly traffic is stored in every street of the map. Traffic-related information is varied; for example the number of vehicles on the road and the real speed of each branch. The evolution of this table is used for the evolution of agents in the street. An example of information on the structure is shown in Figure 5.10.

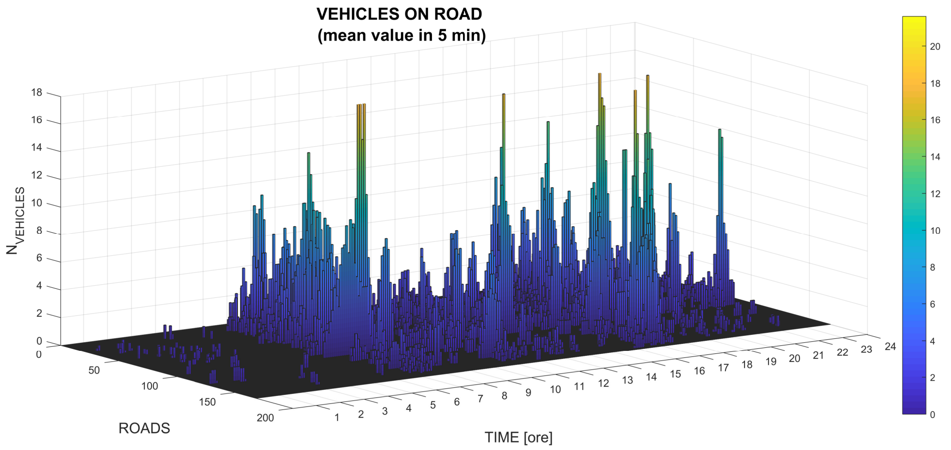


Figure 5.10: Traffic on roads.(1000 drivers, 10% of PEVs user)

- *OUT*, the *"Output"* structure of the temporal loop has the form of *"VEHICLE TRIP"*. In fact, it contains all the information on journeys concluded by the agents. The final information also includes datas such as the total duration of the trip, the consumption, the kilometers traveled, etc. An example of output is shown in Figure 5.11.

Fields	TIME_START	TIME_ARRIVE	VEHICLE	DAY	KM_COVERED	TRAVEL_DURATION_min	NODE_START	NODE_END	EV	DELTA_EN
1	0.1210	0.1667	428	1	0.3915	2.7377	32	74	0	NaN
2	0.4645	0.5833	818	1	7.7656	7.1310	171	24	0	NaN
3	0.2515	0.6333	568	1	7.6345	22.9105	103	64	0	NaN
4	0.6376	0.8333	617	1	4.6657	11.7412	44	3	0	NaN
5	2.2332	2.2667	46	1	0.7829	2.0082	74	42	0	NaN
6	2.4501	2.6500	345	1	8.2226	11.9922	179	32	0	NaN
7	2.4199	2.8000	652	1	9.0056	22.8051	103	212	0	NaN
8	2.9154	2.9500	428	1	0.3915	2.0750	74	32	0	NaN
9	3.1145	3.1500	46	1	0.7829	2.1299	42	74	0	NaN
10	3.2980	3.5500	568	1	7.6345	15.1214	64	103	0	NaN
11	3.2861	3.5833	818	1	6.9827	17.8365	24	210	0	NaN
12	4.3535	4.6833	307	1	8.2226	19.7903	32	208	0	NaN
13	4.4970	4.8167	229	1	5.7427	19.1771	32	187	0	NaN
14	5.4133	5.6833	652	1	9.0056	16.2002	212	103	0	NaN
15	5.4642	5.7500	590	1	5.3513	17.1477	42	187	0	NaN
16	5.5435	5.7500	345	1	4.8287	12.3890	32	120	0	NaN
17	5.5273	5.8500	9034	1	5.7427	19.3629	32	187	1	1.0402
18	5.6831	5.8500	751	1	3.5232	10.0128	107	42	0	NaN
19	6.0957	6.3333	257	1	10.7999	14.2600	143	75	0	NaN
20	6.2400	6.3667	9009	1	9.6574	7.5988	15	120	1	0.4868
21	6.1767	6.3833	818	1	6.9827	12.3971	210	24	0	NaN
22	6.1839	6.5667	52	1	7.6345	22.9643	103	64	0	NaN

Figure 5.11: Example of Output structure.

The temporal loop structure is linked to the creation and progression of the viewed structures over time. It is divided into seven sub-functions. The sorting of these functions is not random but it is very important.

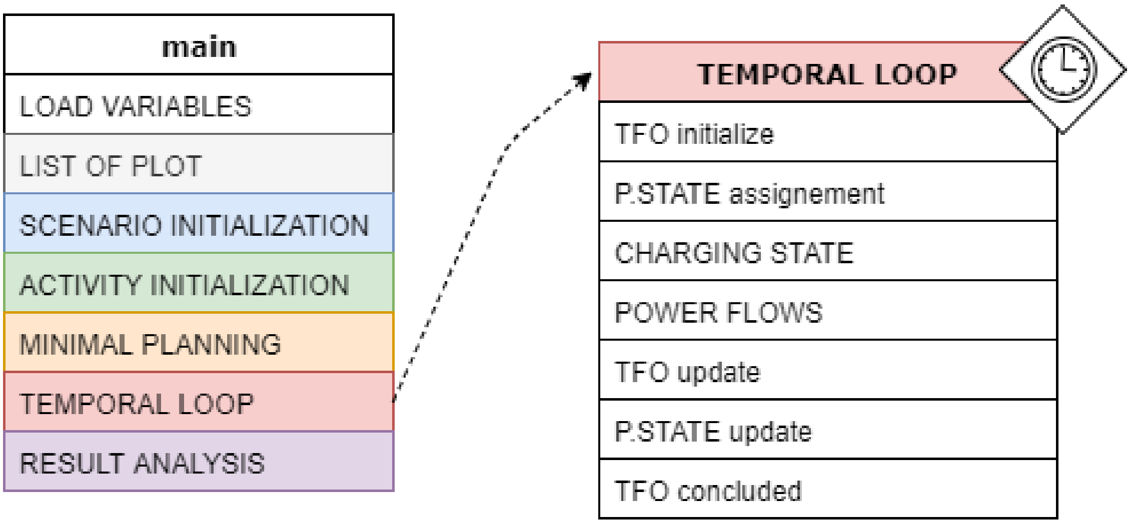


Figure 5.12: Temporal Loop explosed.

The sub-functions, illustrated in Figure 5.12, are the following:

1. *TFO INITIALIZE:* every time window the *VEHICLE TRIP* is read to extrapolate all new trips.
2. *PARKING STATE ASSIGNMENT:* if some new trips are carried out in electric, one of the PEVs present at the "start"node is assigned. In the presence of several vehicles available, the choice falls on the one with the highest SoC. An electric vehicle traveling is not available in any node and the field corresponding to its position assumes the value "inf".
3. *CHARGING STATE:* electric vehicles that are not assigned to any journey (new or previously started) are stationary at the nodes. Every moment they absorb the maximum power available from the charging station, to bring the battery SoC to 100%. The stationary vehicles are therefore loads for the distribution electric network on which they interface and the aggregate power in each node is stored in a specific structure.
4. *POWER FLOWS:* the calculation of power flows is independent of the two networks (semi-urban and rural) and is synchronous with the time cycle. The loads used for computation are the sum of the "conventional"loads plus the loads represented by the recharging PEVs.
5. *TFO UPDATE:* all current journeys are updated. A vehicle travels its "path"passing from one road to another and updates the interactions with the environment. When the vehicle runs out of travel, the 'CONCLUSION' flag is activated.

6. *PARKING STATE UPDATE:* when a PEV ends its journey, it is immediately placed in the 'end' node. It is now available to make new trips. The vehicle SoC is updated by subtracting the energy consumed during the trip.
7. *TFO CONCLUDED:* the trips concluded are eliminated from the structure that contains the trips in progress and stored in the appropriate "OUTPUT"structure. At the end of the simulation it is observed that the TFO structure is empty, while in the OUT structure all the computed trips are present, ordered by the time arrival.

RESULT ANALYSIS The last function in the *main* file is the interpretation and the saving of the results. In the case study, there are many graphs and interesting data to be examined. In fact, only considering the electrical results, we have two independent electrical networks on which to verify that the operational constraint are not violated. In addition to these, it is also interesting to observe the results of the traffic model, of the planning, etc. The most important result of all, however, is to observe how information flows from one layer to another and remains consistent. This shows how the structure used is conceptually very solid.

A graphic summary of what is described is given in Figure 5.13. Starting from the already seen description of the main file, each level has been exploded to show its contents.

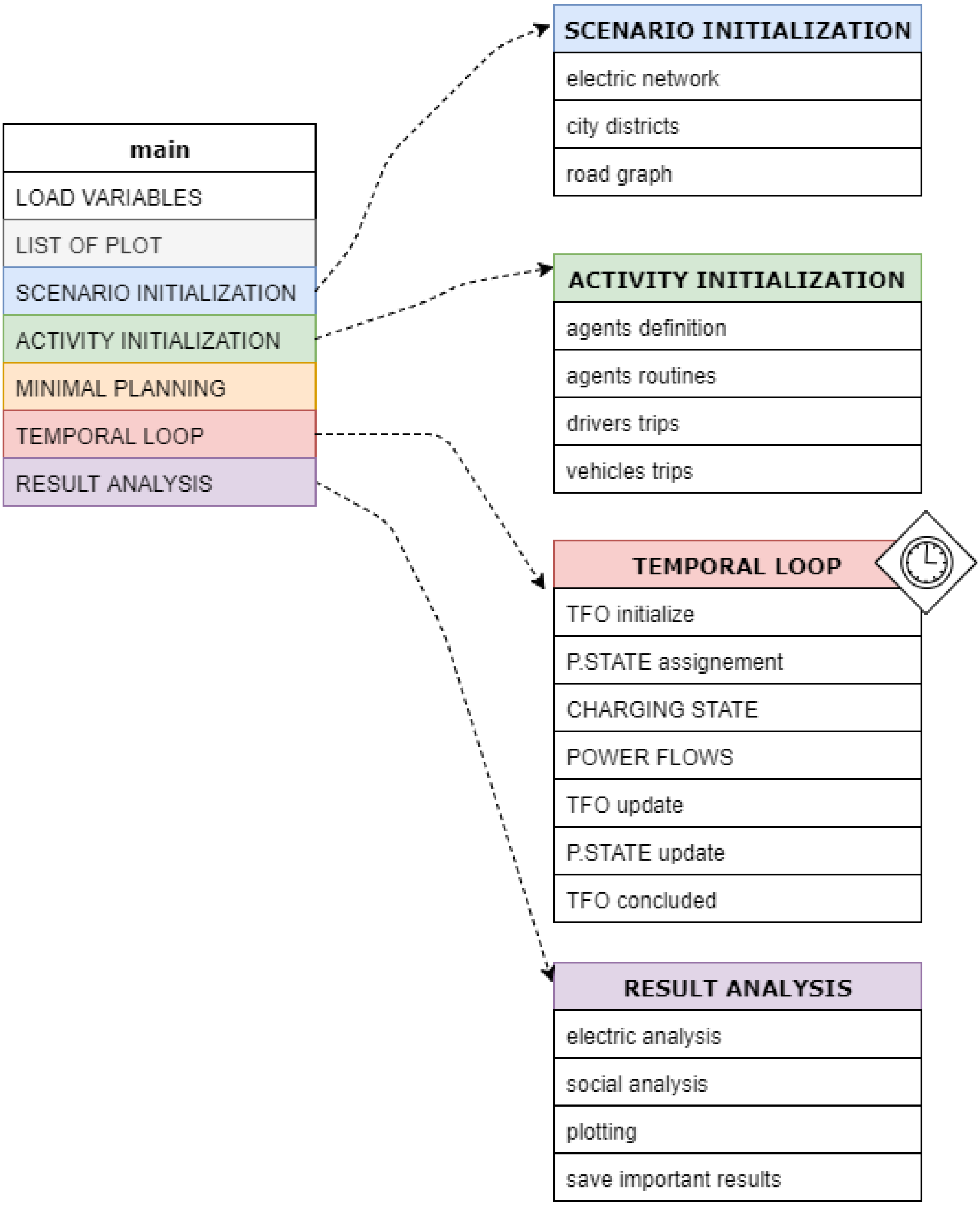


Figure 5.13: Main file exploded.

5.3 Parameters Analysis

Several times it was repeated that the aim of the thesis is to provide a tool for carrying out scenario studies. Once the structure has been created, an additional tool has been created that allows the sequential execution of the IT processes of Figure 5.13 completely automatically. In fact, as expected, the increase in the simulated population corresponds to an increase in computation times. The processes that require greater computational capacity are identified in the *planning*, in the *temporal loop* (in which the time cycle and the agent cycle are nested) and in the *plot* of the results. The times of computation in relation to the number of agents is shown in Figure 5.14:

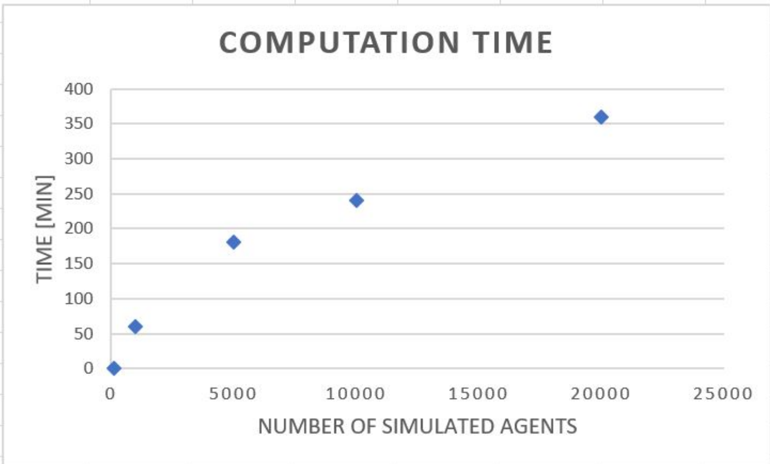


Figure 5.14: Computation times in relation to the number of simulated agents.

The realization of a parametrized analysis meets the need to obtain the results of the simulation in different scenarios, in the shortest time possible. Among all the main variables of the program (see page 71), some of these are considered more significant. A variable is identified as *meaningful* if it matches two criteria:

- Considering its variation could have a strong impact on the final results
- Its variation is consistent with realistic scenarios

Thus, for example, the number of simulated agents can be considered significant, and temporal variables are not considered significant.

The variables analyzed with the parametric analysis are shown in table 5.1:

The parametric analysis performed is of two-dimensional type (2D). In fact, the table from Excel is read in which the quoted variables and the respective values are contained. The tool proceeds by carrying out the complete study with respect to any possible combinations of the indicated values.

- *N DRIVERS* The number of simulated agents is obviously the parameter that most influences the simulation. A larger number of agents means in fact a greater number of PEVs (of loads for the network).

Table 5.1: Parameters analysis.

N DRIVERS	% EV USER	ROAD TYPE	POWER STATION [kW]
1000	10	GOOD	3
5000	30	BAD	6
10000	60		11
20000			

- *% EV USER* The percentage of users of the electric car-sharing service does not have a direct relationship with the number of simulated PEVs. In fact the addition in the initial planning model reduces a little the total number of electric vehicles (e.g., with 5000 agents and 10% of users of the car sharing service, the number of simulated PEVs is 320, instead of 500).

- *ROAD TYPE* The use of two scenarios, one with roads as indicated in table 4.1 and one considering worst roads could have an impact on the electricity grid. In fact we want to check which impact on the results could have a longer residence time on the street (and consequent increase of the energy lost for the movement). The parameters associated with bad roads are shown in table 5.2:

  Table 5.2: Bad roads characteristics.

ROAD TYPE	U_F	K_C	K_J	3σ
BAD ROAD	10	4	11	2

- *POWER STATION* The study of the maximum power that can be supplied by the charging stations wants to highlight how the absorption profiles of PEVs are modified. It is indeed logical to expect that the total absorbed energy remains unchanged, while the load peaks can shift temporally.

The process of selecting the variables used for the simulation is included in the *LOAD VARIABLES* step of Figure 5.4. The total number of permutations is obtained progressively using the Matlab *combvec ()* function. In this way a matrix is obtained which, read by rows, contains the value to be assigned to the variables for the current simulation.

The total combinations obtained from the proposed analysis are 72.

5.3.1 Scenarios

Among all the possible combinations, it was decided to highlight those considered most significant. The simulations analyzed below are divided mainly into two categories:

- Simulations with limited number of agents.

- Simulations with a high number of agents.

For the study and develop of the model used, it is essential to initially reduce the number of random variables at stake. In this way it is possible to check each step of the program illustrated above.
The objective of a study with a limited number of agents is therefore not to evaluate the effects on the network (as we will see this effect is minimal) but it is to evaluate the correct flow of information between the levels proposed (Figure 5.1).

Simulations with limited number of agents.

As explained, the objective of this analysis is to verify the correct flow of information between the proposed levels. A limited number of agents make it easier to follow the "tracks"left by each agent, starting from the decision-making level up to the dynamic component of the electricity grid. Compared to the size of the map used (about $240[km^2]$), and to the characteristics of the global distribution system, a population of 23000 vehicles is estimated. This value is obtained in several steps:

- From the residential powers of each electrical node the number of households is estimated, counting the number of contracts from 3 [kW] (reference for a domestic meter) served by the networks:

$$\begin{cases} P_{\text{res,SEMI}} = 44[MW] \rightarrow 15000 & \text{contracts of 3 [kW]} \\ P_{\text{res,RUR}} = 2.7[MW] \rightarrow 1000 & \text{contracts of 3 [kW]} \end{cases} \tag{5.1}$$

$$Population_{\text{TOT}} = 16000 \text{ family units} \tag{5.2}$$

- From the ISTAT 2017 data ([24]), we obtain the average number of members of a family unit in Italy:

$$\text{average number of people per household} = 2.4 \text{ (Italy)} \tag{5.3}$$

- Finally, from the statistics of the Italian municipalities ([25]), we get the number of vehicles circulating in a municipality of extension comparable to the city used in the scenario (municipality of reference, Cuneo center)

$$\text{Cars per capita for the municipality of Cuneo} = 0.6 \tag{5.4}$$

- In this way the estimate of the population of cars circulating in the map is obtained.

$$Vehicles_{\text{TOT}} = 23000 \tag{5.5}$$

simulation with 1000 agents

This simulation is considered as a reference for reading simulations with large numbers of agents. The speed of computation and the ease of reading a limited number of variables, makes this simulation particularly effective as a guide for reading the results. The results are proposed following the proposed logic of the layers and the schematic division of the tool, illustrated previously in Figure 5.12. The results are illustrated starting from Figure 5.15 up to Figure 5.30. The graphs are divided into:

Scenario Initialization The graphs shown, referred to the simulated environment, are the same for each simulation performed. The city map is not a variable for the parametric study. The passage from the electricity grid to the road network is illustrated in Figure 5.6.

Activity Initialization The second step of the program aims to create a population of heterogeneous agents among themselves. Each agent, as seen in *Chapter 3*, is characterized by numerous parameters. The most significant are surely the knowledge of the node in which they live and the knowledge of the nodes in which they perform the actions during the day. The result of the IT object is the list of trips of each agent, obtained starting from the weekly routine assigned to them and from the extraction of journeys (considering arrival flexibility and eventual delays). The results are shown from Figure 5.19 to 5.21.

Minimal Planning The planning, as explained in *Section 5.2*, has the purpose of minimizing the number of PEVs circulating in the map. This step has two objectives: to make the car sharing scenario more realistic (the owner of the service will want to reduce as much as possible the number of vehicles to be purchased) and increase the average consumption of each car. If the availability of vehicles at the nodes is limited, the same vehicle will carry out an average number of trips, with a consequent decrease in the SoC level. The result of planning is shown in Figure 5.22.

Temporal Loop In the temporal loop, the impact of the vehicles in charge on the distribution networks is calculated, in real-time with the evolution of the model. As explained previously, in the model there are two different electrical distribution networks. The study of these two networks is done independently because it is considered an ideal external transmission network. For each network the power flow is calculated via *Backward-Forward Sweep* Method. The network constraints are evaluated in the presence and absence of vehicles. The main parameters observed are:

- Currents at the nodes, Figure 5.25 and Figure 5.26;
- Voltage at the nodes, Figure 5.27 and Figure 5.28;
- Currents in the branches, Figure 5.29 and Figure 5.30;

It is also interesting to observe the impact of the variables of the parametric analysis on the evolution of the model. For example, the effects of significant traffic parameters and how this propagates on the electrical level can be seen .

As anticipated, the results of the tool with an underestimated population of agent have the value of looking for errors in the model. As can be seen from the figures below, the additional loads caused by the recharging PEVs, are of an order of magnitude lower than the *conventional loads*. Conventional loads are obtained from "standard" load profiles (see *section 4.1*).

Simulation with 5000 and 10000 agents

The intermediate scenarios between the conceptual study of the problem and the quantitative study are carried out in order to follow the evolution of the proposed results in a continuous way. The study on 1000 agents showed that:

- The rural network is electrically weaker than the semi-urban network. This may depend on the value of the line parameters (higher losses) and the lower nominal powers of the nodes.
- Following what has been said in the previous point, a small percentage of electric vehicle journeys to the outskirts of the city can cause, as the number of vehicles increases, exceeding the network operating constraints.
- The presence of some highly attractive city nodes in the rural network causes the movement of agents. However, the agents do not deposit vehicles in nodes with high installed nominal power but in close (weaker) nodes.
- Of all the network constraints analyzed, the currents in the branches are the most sensitive to the presence of vehicles.

The simulation with 5000 and 10000 agents confirm what we have seen with 1000 agents, allowing us to focus our attention on the most significant results. The results are illustrated starting from Figure 5.31 and Figure 5.32.

simulation with 15000 and 20000 agents

The simulations with 15000-20000 agents represents the most significant case study. In fact, according to what has been previously seen, they represent the population's estimate of the city. According to what has been learned from the simulations with a limited number of agents, we have focused on the search for possible violations of the restrictions on the rural network. Furthermore, the impact of additional variables such as the power of charging stations on the networks was observed. The results are illustrated starting from Figure 5.33 up to Figure 5.35.

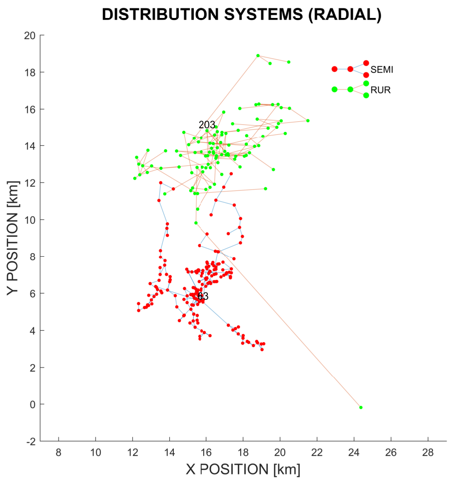


Figure 5.15: Starting electrical networks (semi-urban and rural).

5.3.2 Comparison between scenarios

This section highlights the significant variations of the observed parameters, as the number of simulated agents increases. This approach allows to evaluate only the occurrences of the most significant events of the entire simulation to compare the different scenarios. Figure 5.36 shows the increase of the maximum voltage drop in the semi-urban and rural networks. The Figure 5.37 shows instead the impact of the maximum power of the charging sockets. It is observed that the impact of the installed power of the charging stations has an increasing effect on the maximum voltage drop.

The results of clustering through the k-means algorithm are shown in Figure 5.16. From the electrical nodes the citizen nodes (neighborhoods) equivalent are obtained.

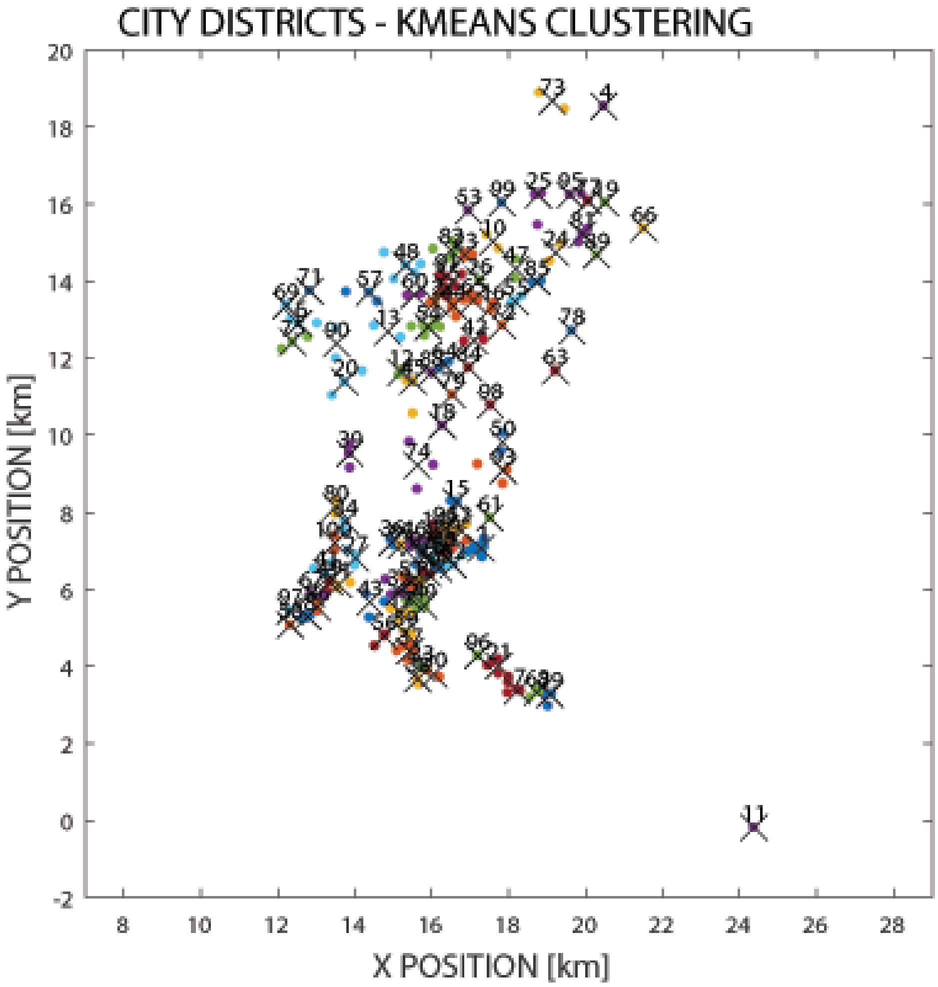
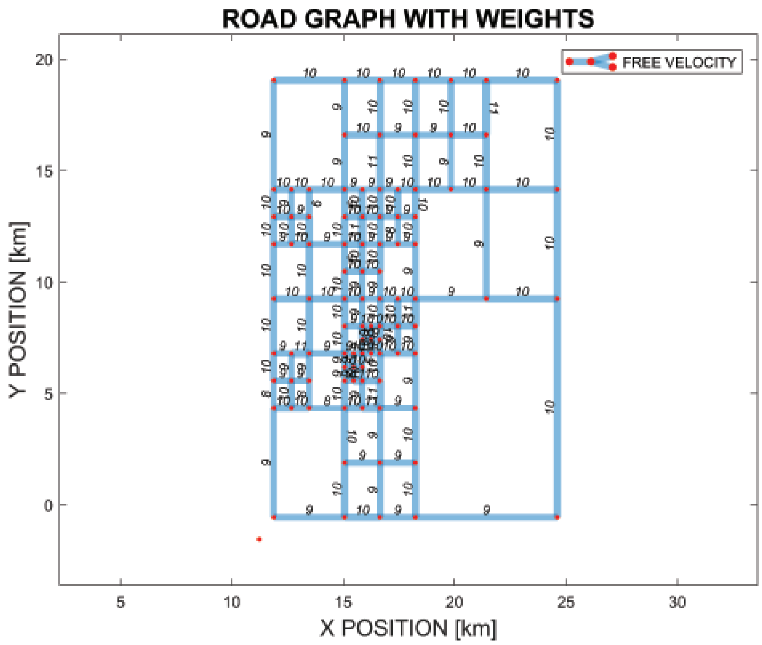


Figure 5.16: Citizen nodes

The road map is indicate in Figure 5.17. On every stretch of road the speed of travel is indicated in the absence of traffic. On the knowledge of these speeds the agent chooses the fastest route. In detail the two possible scenarios are shown: beautiful roads or bad roads.



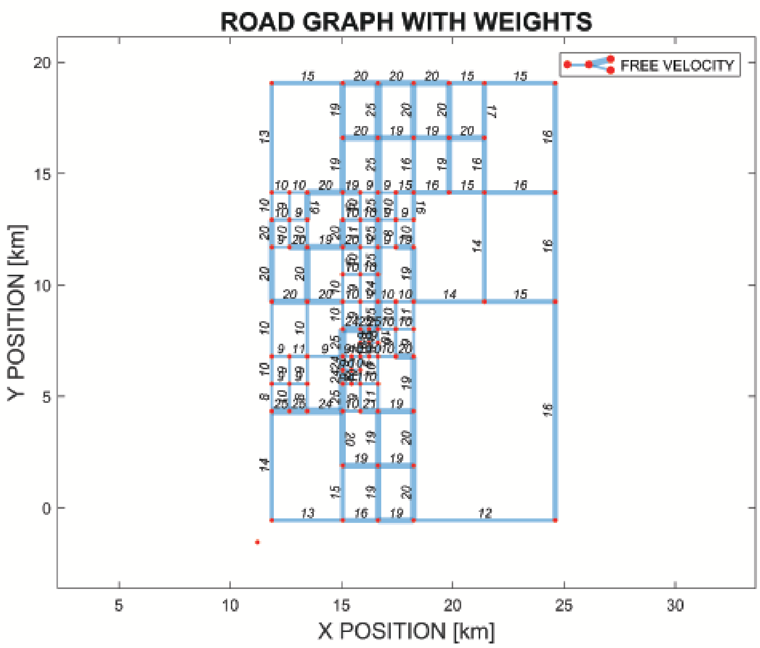


Figure 5.17: Road map

The CDF of the roads length is shown in Figure 5.18. It is observed that eighty percent of the roads are less than two kilometers long.

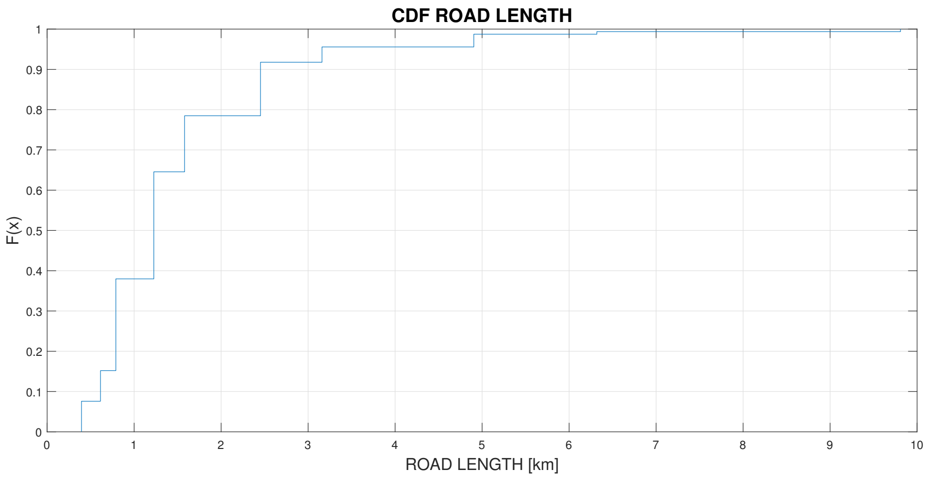


Figure 5.18: CDF roads length.

The sodes where agents live are presented in Figure 5.19. It is evident that the city center is attractive for the residence of agents. This comes from residential powers to nodes, greater for the semi-urban network.

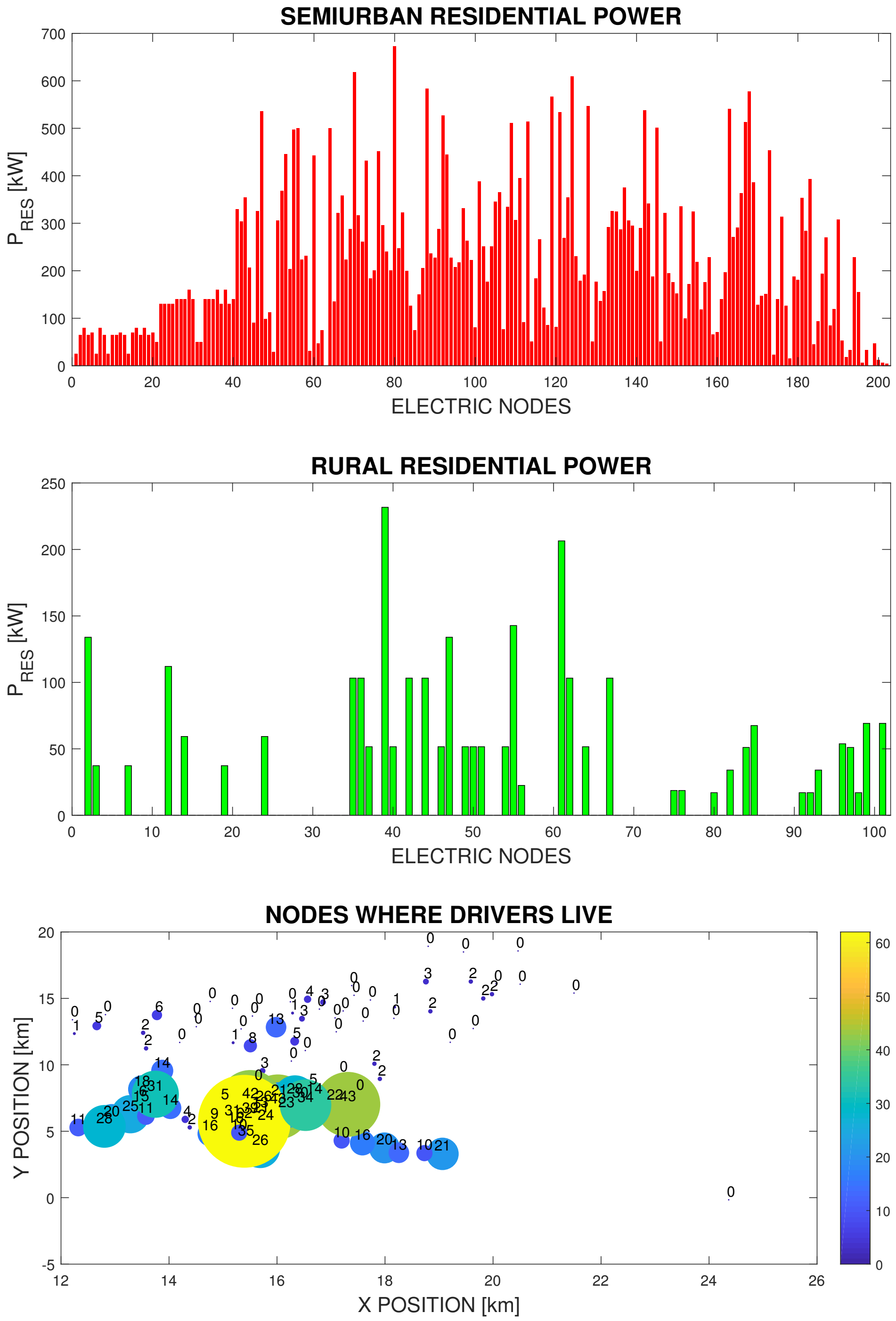


Figure 5.19: Nodes where agents live.

The nodes where agents work are shown in Figure 5.20. As for the attractiveness to working nodes, the rural network is comparable to the semi-urban one. In particular, we note the presence of some nodes with very high nominal power in the rural network. This suggests the presence of a large-scale industrial activity (e.g., a factory).

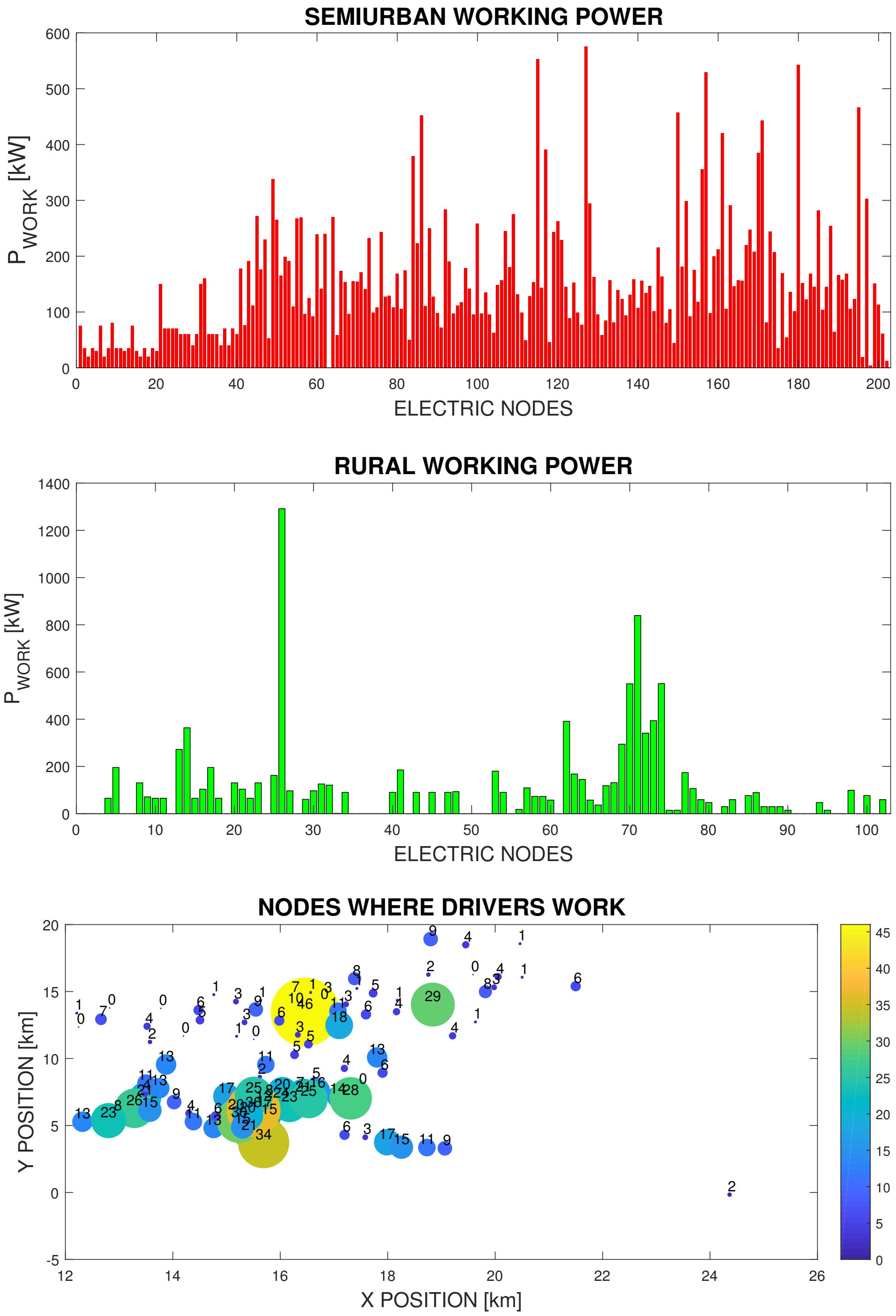


Figure 5.20: Nodes where agents work.

Figure 5.21 shows the complete weekly routine of agent 1. This agent is characterized by a Gaussian distribution for delay extraction with mean value $0[min]$ and standard deviation $30[min]$. It is observed that this agent is working in the agricultural sector and has full-time employment. In the lunch break the agent does not return home but remains at work and, on the Sunday of the simulated week, is out of town.

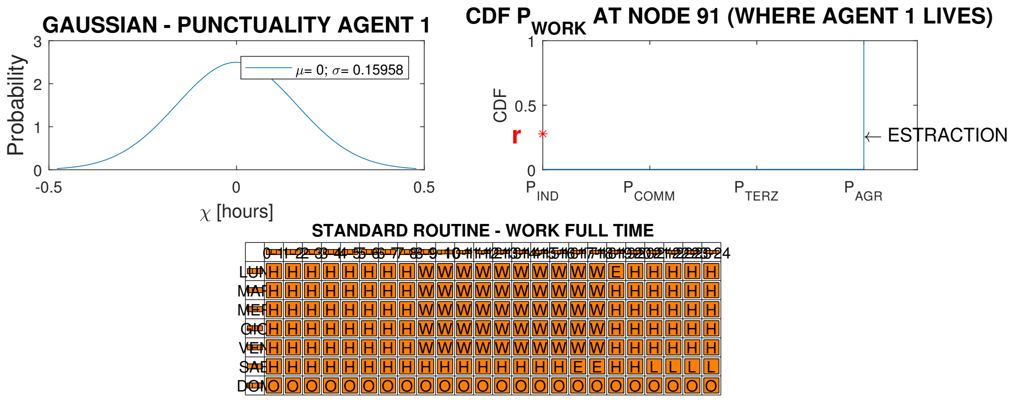


Figure 5.21: Weekly routine of agent 1.

Figure 5.22 shows the effect of the planning with different penetration of use of the electric car sharing service. The number of vehicles in each road node is shown at the beginning of the simulation. This initial condition allows the conduct of each weekly trip.

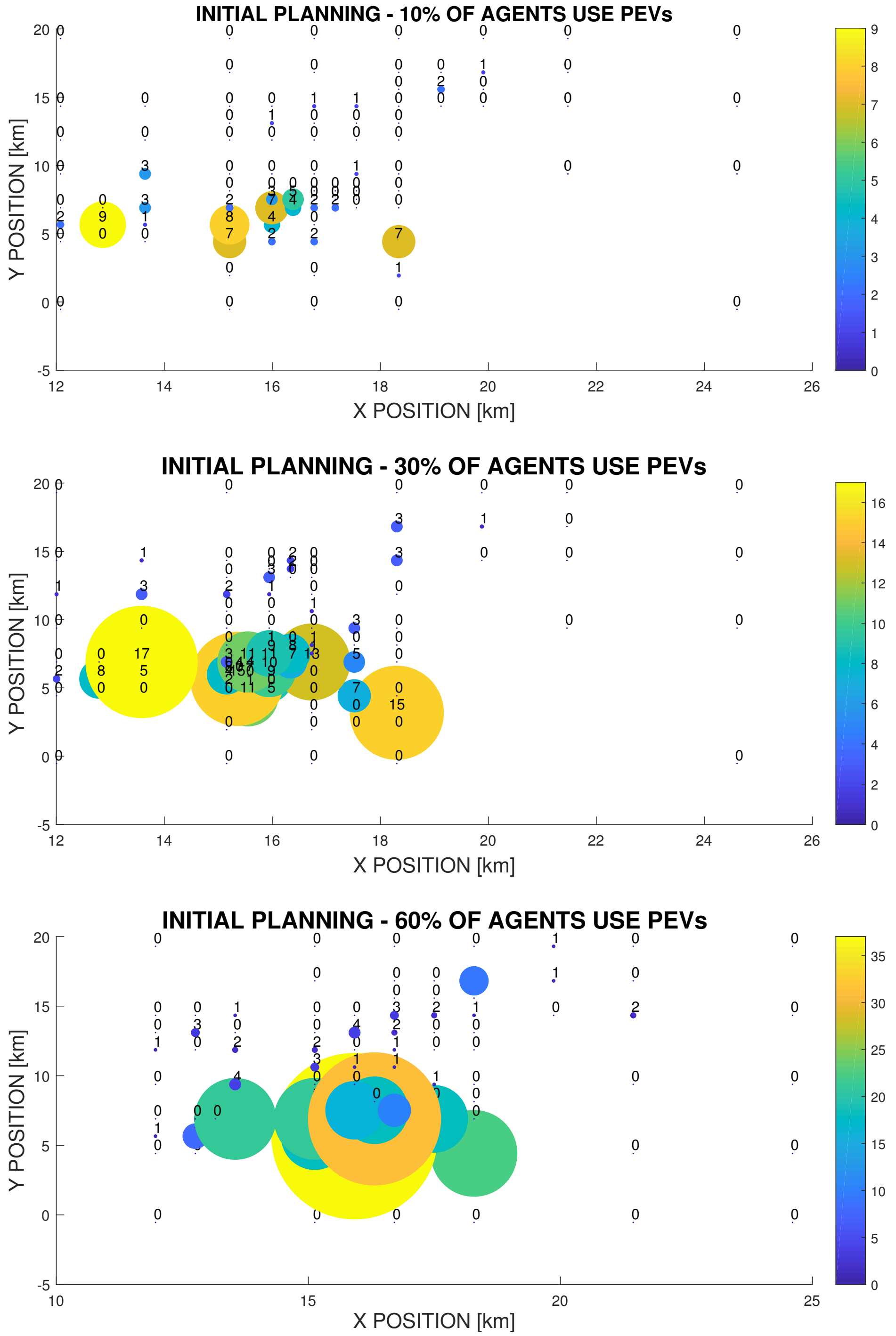


Figure 5.22: Effect of the planning (1000 drivers)

Figure ?? presents the load profiles applied to the semi-urban network. It is noted that the recharge profile of the PEVs is very fragmented and of an order of magnitude lower than the loads normally applied on the network. This indicates that occurrences are rare in which most vehicles are recharged simultaneously in the same node. Charging station = 11 [kW]

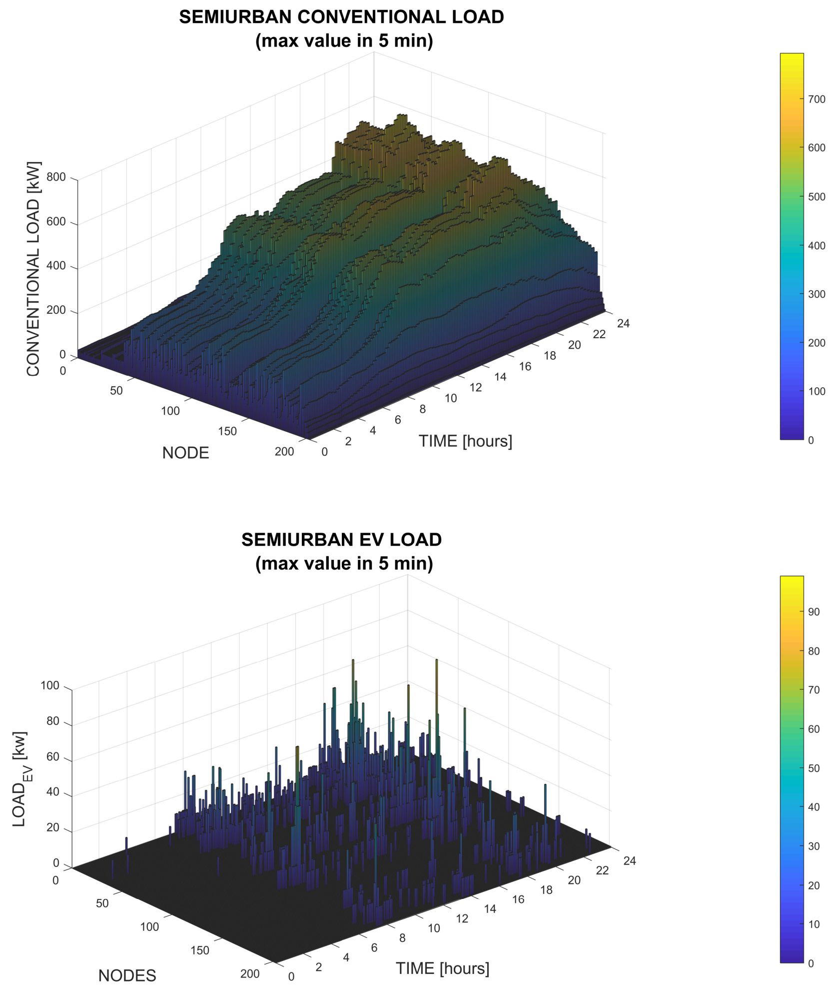


Figure 5.23: Load profiles applied to the semi-urban network (1000 drivers).

Figure 5.24 presents the load profiles applied to the rural network. It is observed that the profile imposed by the PEVs is consistent with the observations of the social layer. In fact, it is clear how trips to the rural network (less attractive for agents) are less frequent. Recharge observed on rural nodes occur, consistently with what is observed, mainly in the morning when the agents go to work. The electrical nodes in which most of the agents leave the vehicle do not correspond to the node with greater nominal power installed but are geographically close. In fact, the trips do not take place towards the electrical nodes but towards the road nodes as illustrated in *Chapter 3*. Charging station = 11 [kW]

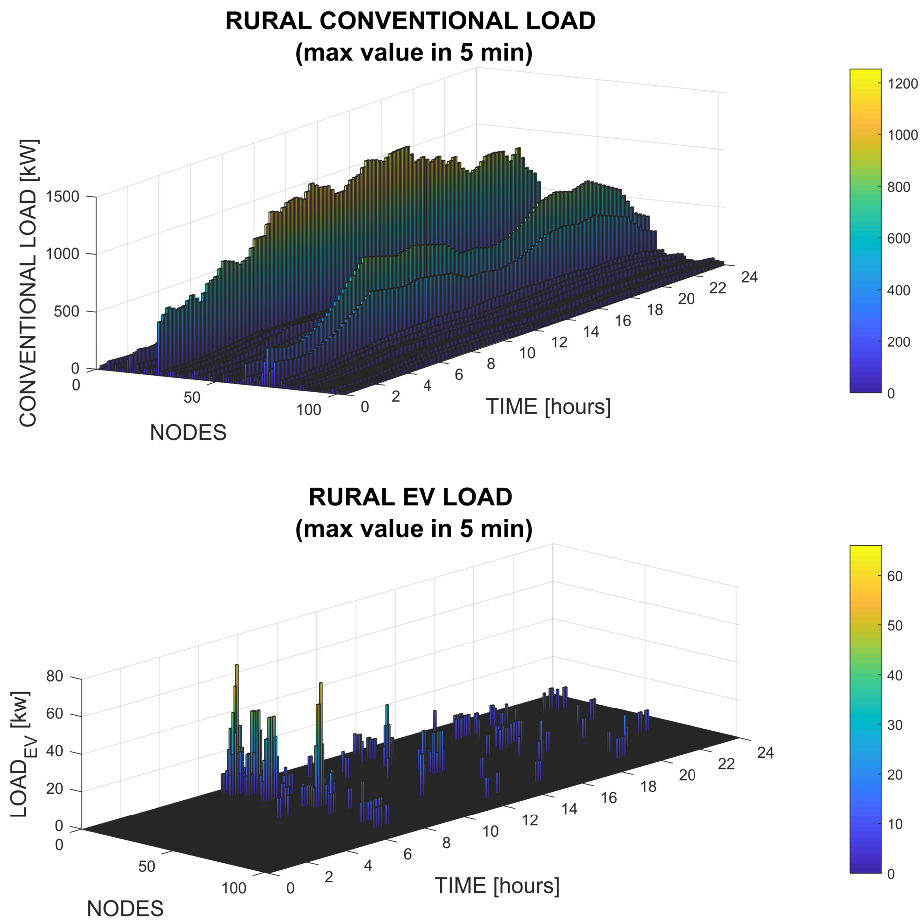


Figure 5.24: Load profiles applied to the rural network (1000 drivers).

Figure 5.25 plots the semiurban nodal current and increase of nodal current caused by the presence of PEVs. The nodal current is calculated directly from the nodal loads. The report, used for the Forward phase of the BFS method, is shown in *Chapter 2*. It is observed that the increase in current at the nodes due to the vehicles being charged, for such low numbers is very low (1000 drivers).

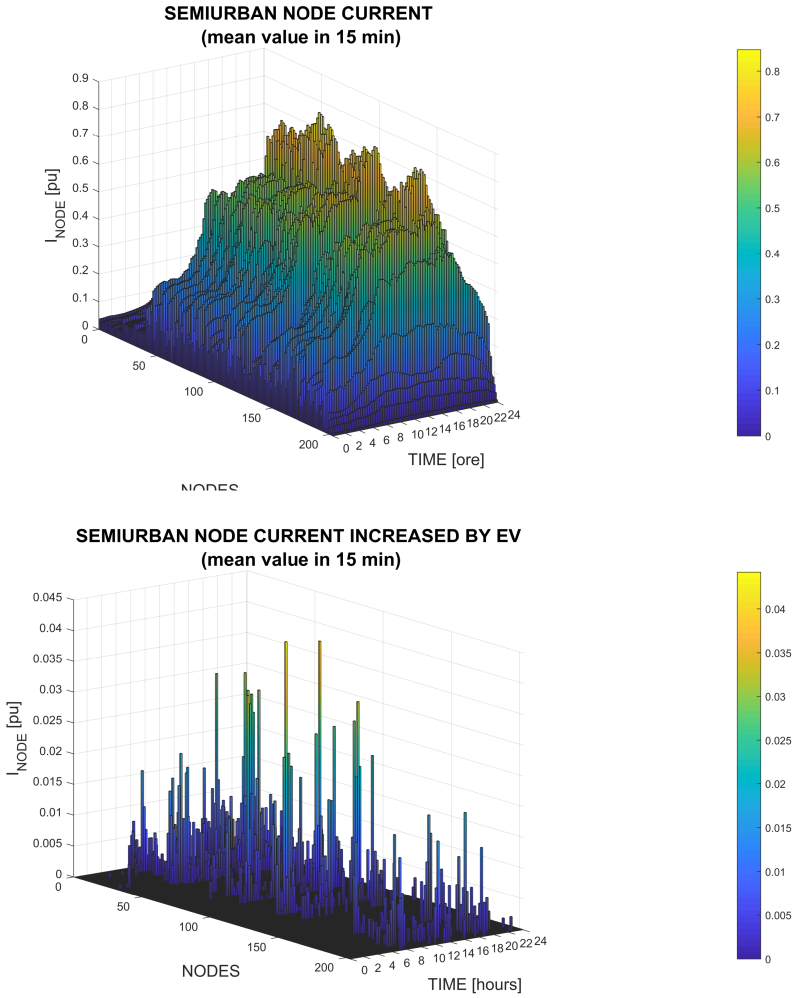


Figure 5.25: Semiurban nodal current and increase of nodal current caused by the presence of PEVs.

Figure 5.26 plots the semiurban nodal current and the increase of nodal current caused by the presence of PEVs. It is observed that on the rural network, even in the presence of added loads much lower than the semi-urban network, the quantitative impact of the PEVs is substantially equal to the semi-urban network. There is some evidence of a weakness (albeit still largely marginalized) of the urban network in the presence of additional loads.

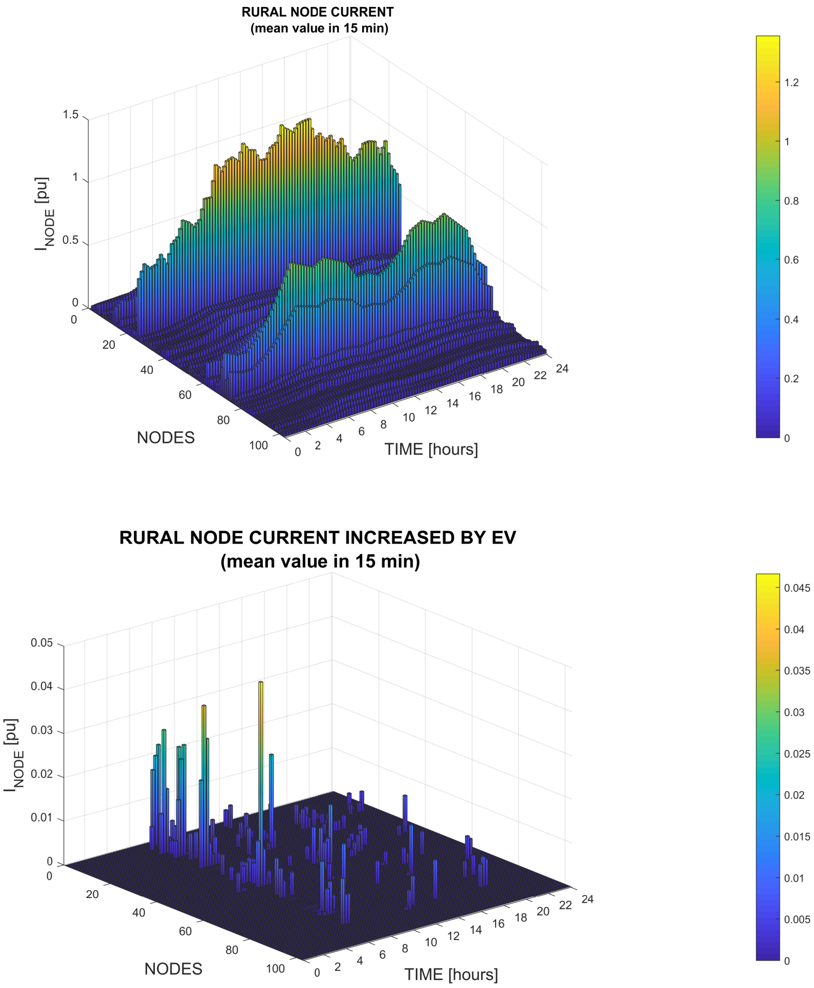
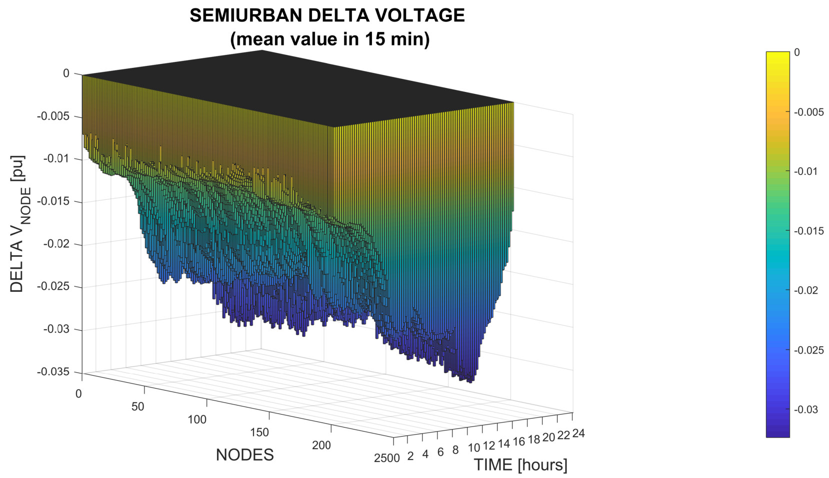


Figure 5.26: Semiurban nodal current and increase of nodal current caused by the presence of PEVs.

Figure 5.27 shows the voltage drop on the semi-urban network. It is observed that the semi-urban network under standard operating conditions (without significant additional loads) never goes into conditions of overcoming network constraints. The voltage drops at the nodes are negligible.



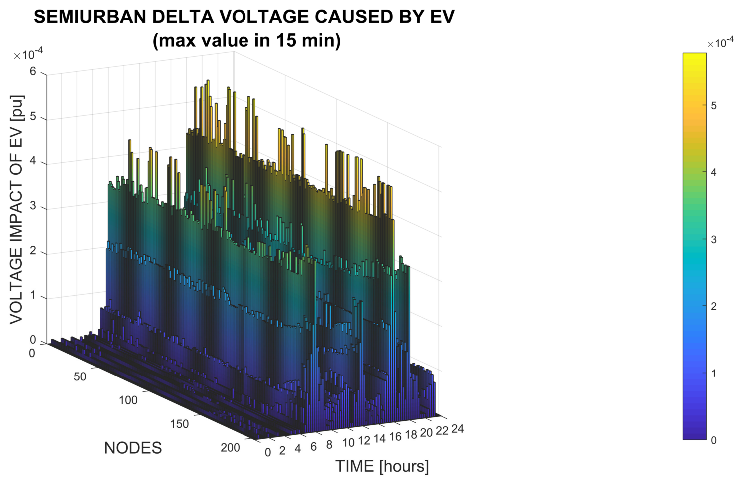


Figure 5.27: Voltage drop on the semi-urban network (1000 drivers).

Figure 5.28 indicates the voltage drop on the rural network. Even the rural network, with penetration of very low additional loads, operates in ordinary conditions, without straining the voltage constraints.

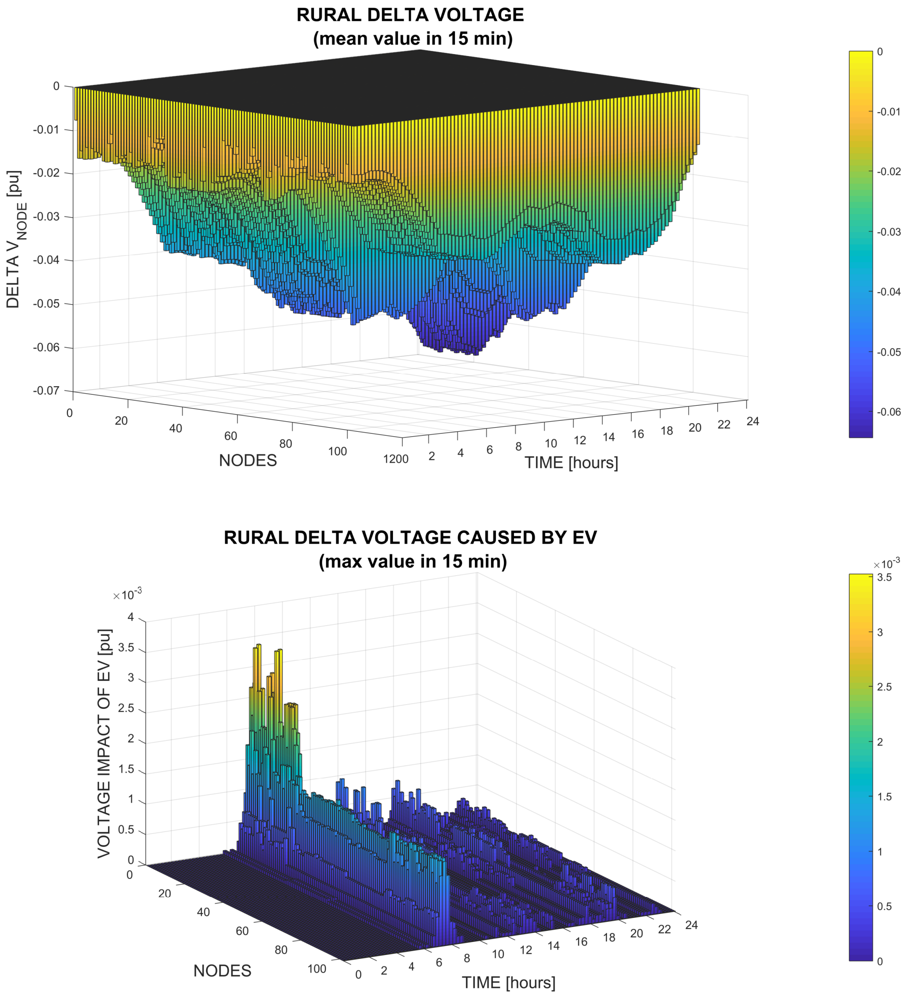


Figure 5.28: Voltage drop on the rural network (1000 drivers).

Figure 5.29 indicates the current in the branches for the semi-urban network. The impact of a limited number of PEVs is always minimal from a quantitative point of view. However, it is evident that among all the results obtained, the increase in currents in the branches is the most significant. It is understood that compliance with the thermal constraints of the lines could be the network constraint that will be more solicited by greater penetrations.

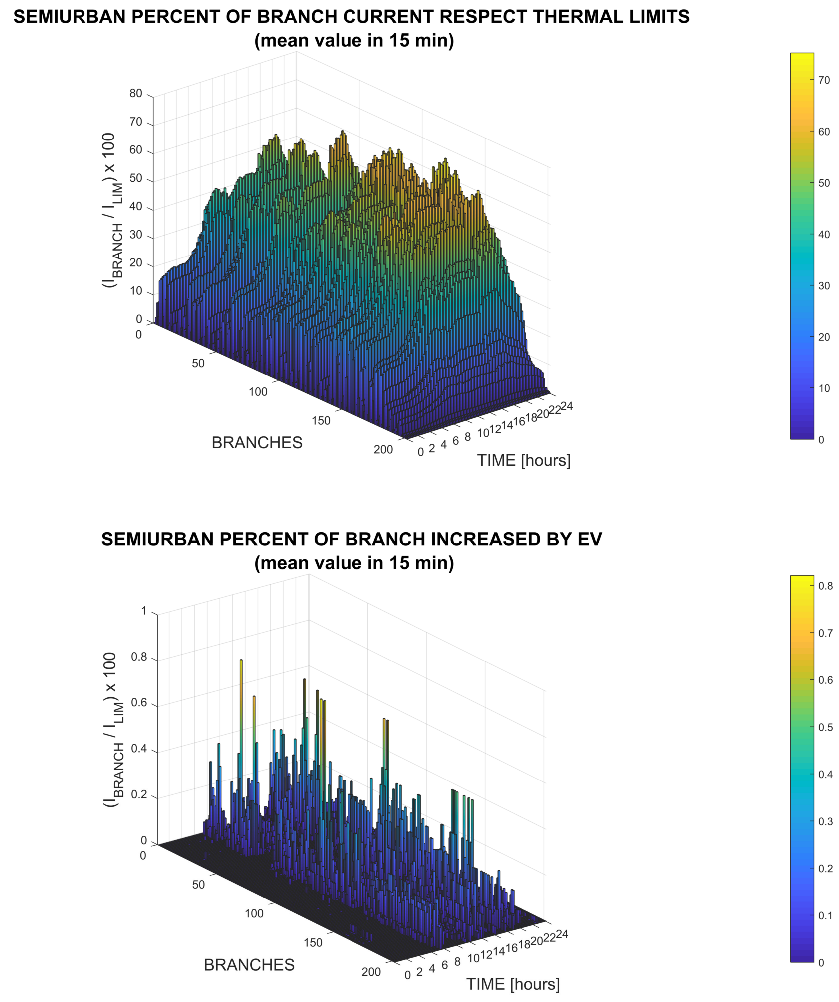


Figure 5.29: Current in the branches for the semi-urban network (1000 drivers).

Figure 5.30 shows the current in branches for the rural network. The rural network is weaker than the semi-urban network. In fact, it is recalled that the number of PEV loads on the rural network is lower than those applied to the semi-urban network. Despite this the increase in currents in the branches is double (always in correspondence of the branches that lead to the nodes with higher power and in times with greater traffic).

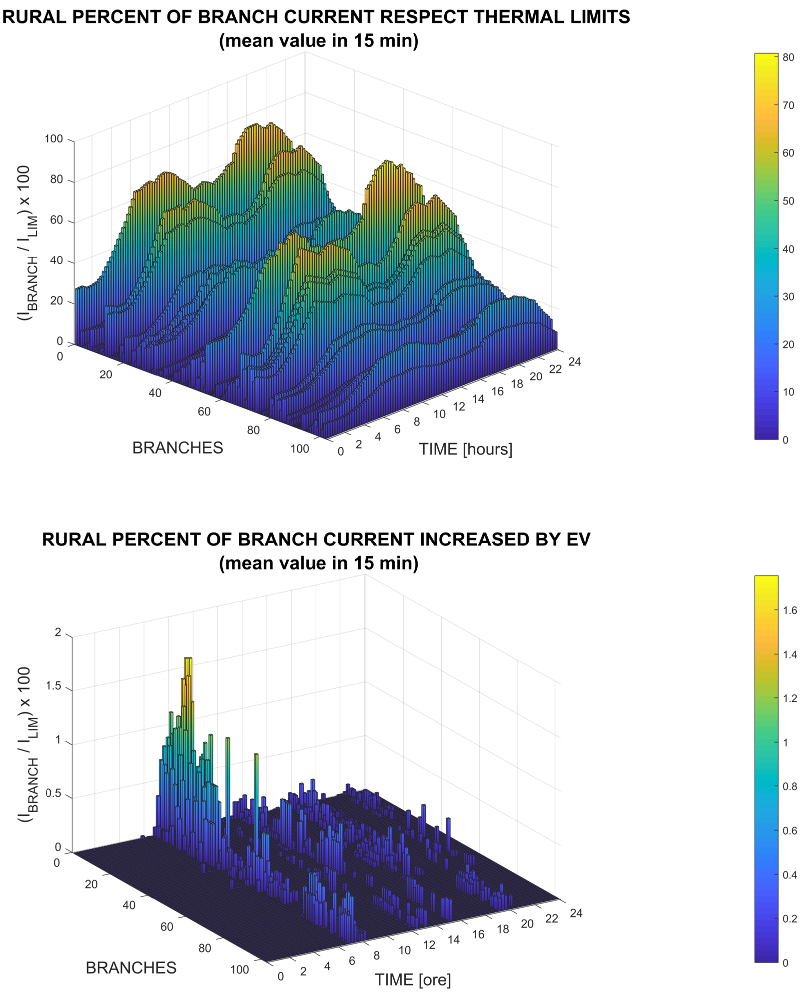


Figure 5.30: Current in branches for the rural network (1000 drivers).

From Figure 5.31, it is noted that the distribution of loads applied to the two networks is always very unbalanced. However, as the number of agents increases, the additional load on the rural network increases significantly. Charging station = 11 [kW]

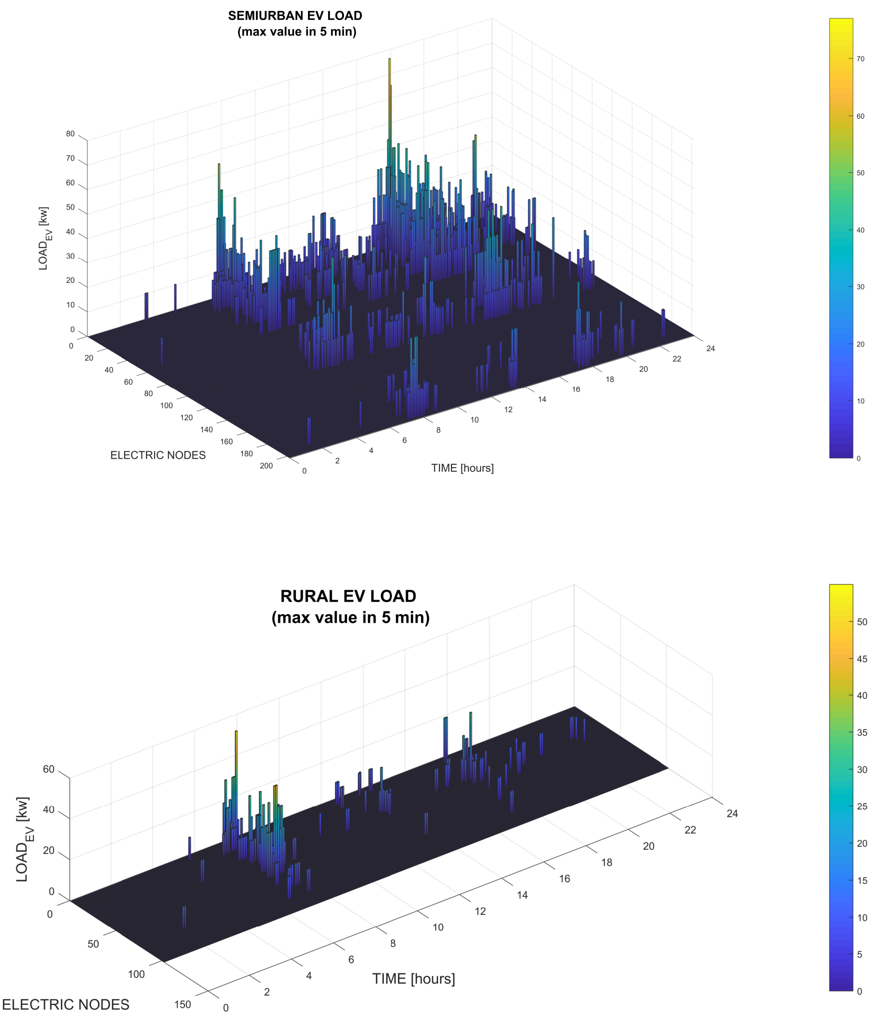
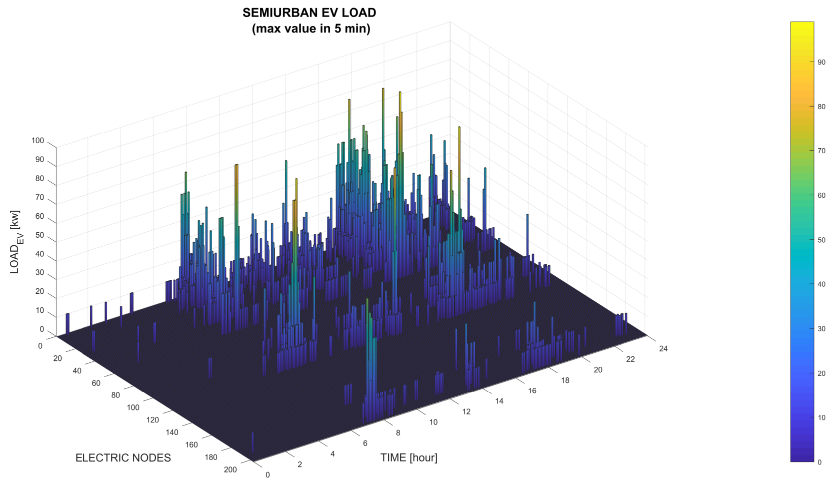


Figure 5.31: Load PEVs profiles applied to the networks (5000 drivers).

From Figure 5.32, with 10000 drivers, charge peaks are observed even at night. This is the effect of the proportion of random agents, which becomes significant when the number of agents becomes large. Charging station = 11 [kW]



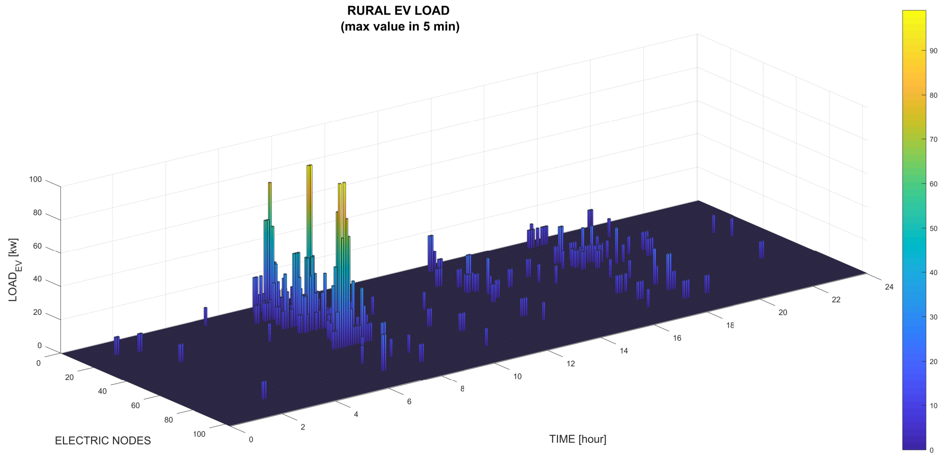


Figure 5.32: Load PEVs profiles applied to the networks (10000 drivers).

From Figure 5.33, with 10000 drivers, charge peaks are observed even at night. This is the effect of the proportion of random agents, which becomes significant when the number of agents becomes large. Charging station = 11 [kW]

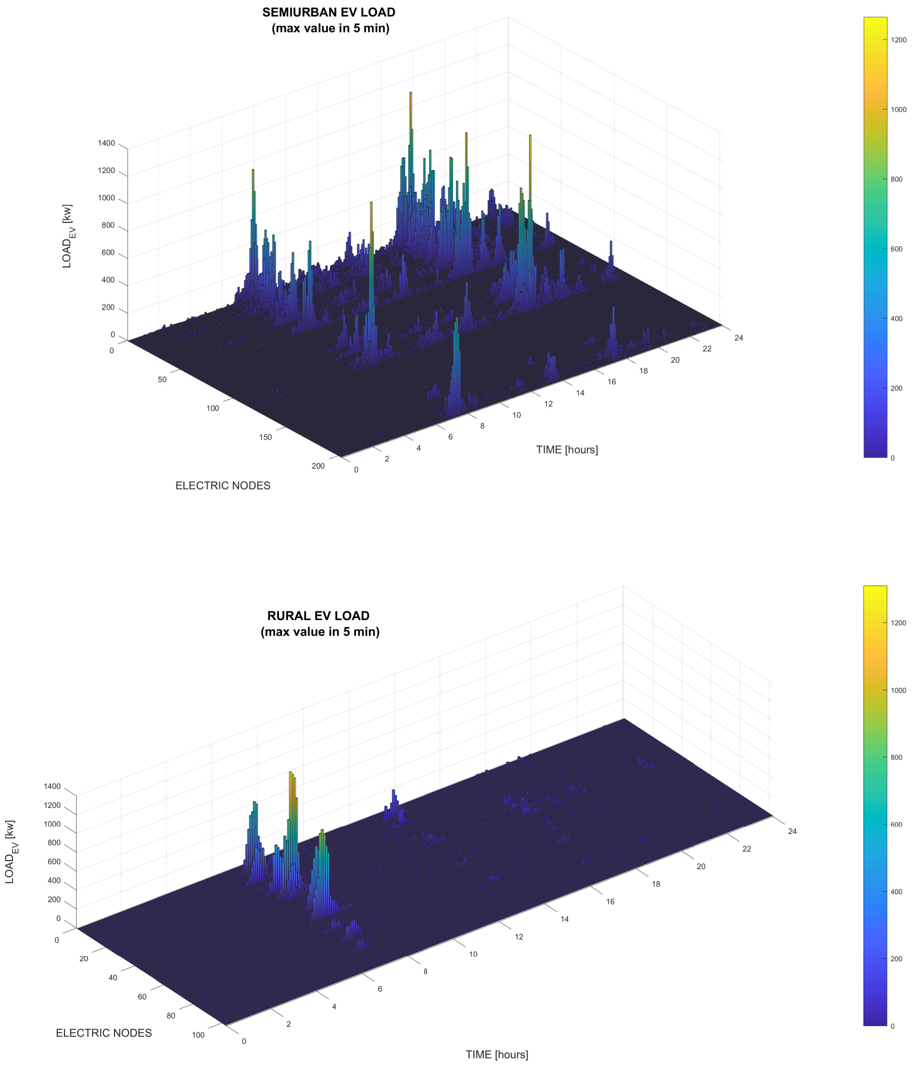


Figure 5.33: Load PEVs profiles applied to the networks (20000 drivers).

From Figure 5.34, according to previous studies, from the point of view of voltage drop the impact of vehicles on the distribution system does not cause technical problems. It is observed that the most requested network is always the rural one. Charging station = 11 [kW]

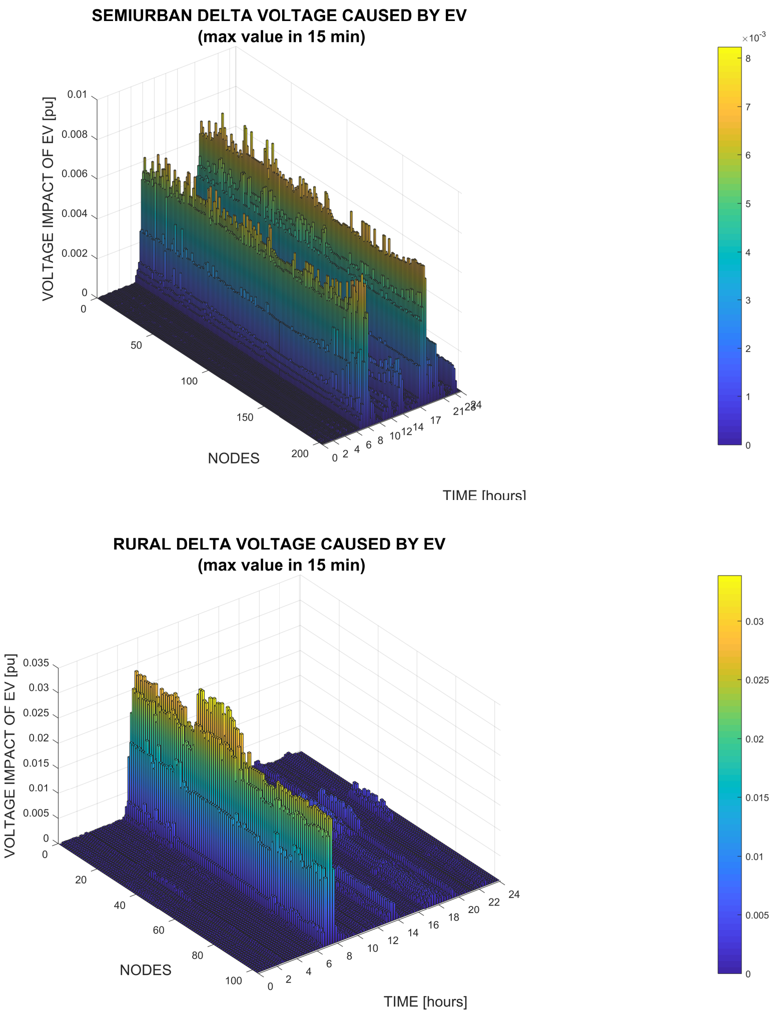


Figure 5.34: Voltage drop caused by the presence of PEVs (20000 drivers).

From Figure 5.35, it is observed that the increase due to the presence of vehicles is clearly visible also in the aggregate effect. The contemporaneousness of conventional loads and PEVs loads does not create overloads on the network, but creates peak usage levels of more than 90% of the conductors during the hours when agents go to work (Charging station = 11 [kW]).

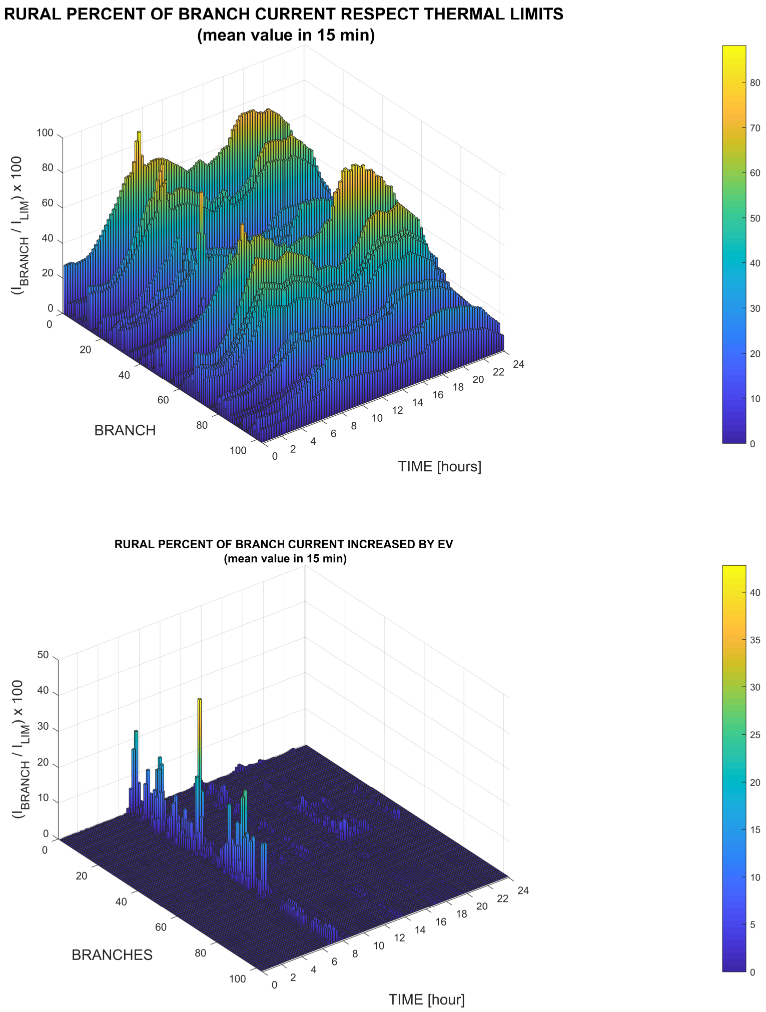


Figure 5.35: Current in the branches of the rural network (20000 drivers).

From Figure 5.36, it is observed how, by increasing the number of simulated agents, the trend of voltage drops on the rural network follows an exponential trend. Charging station = 11 [kW]

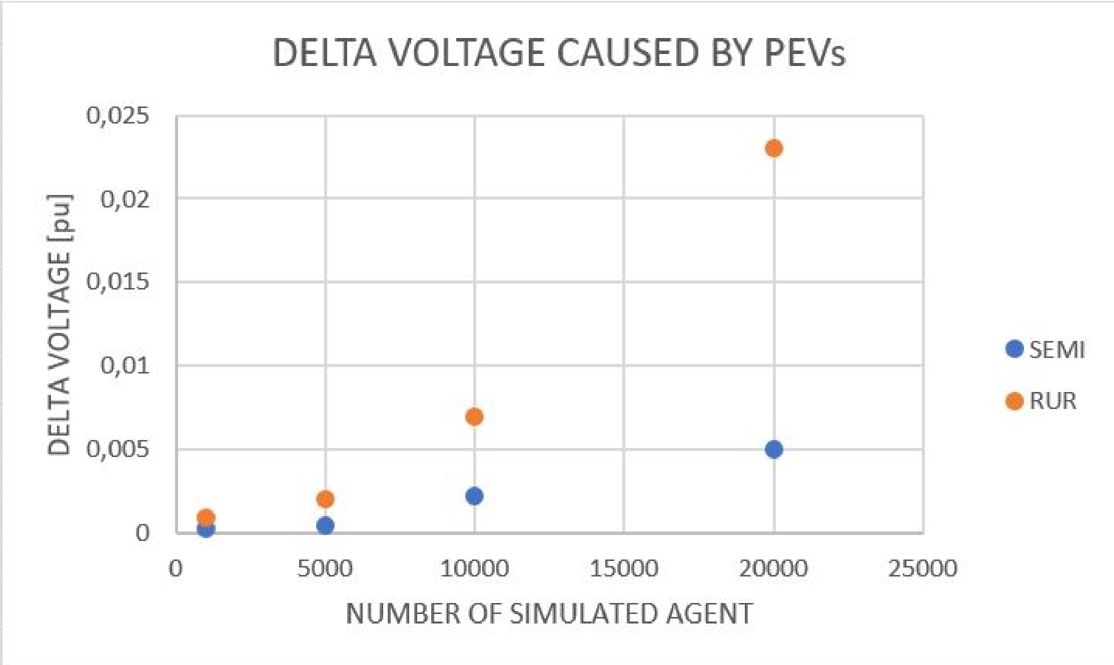


Figure 5.36: Maximum voltage drop on the networks vs number of agents (Charging station = 11 [kW]).

Figure 5.37 shows the impact of the installed power for the charging sockets has a limited impact on the voltage at the nodes. This is because the impact of vehicles is mainly due to the contemporaneous nature of vehicles in charge. If in a node the number of cars is still limited, the overall effect has little dependence on the power absorbed.

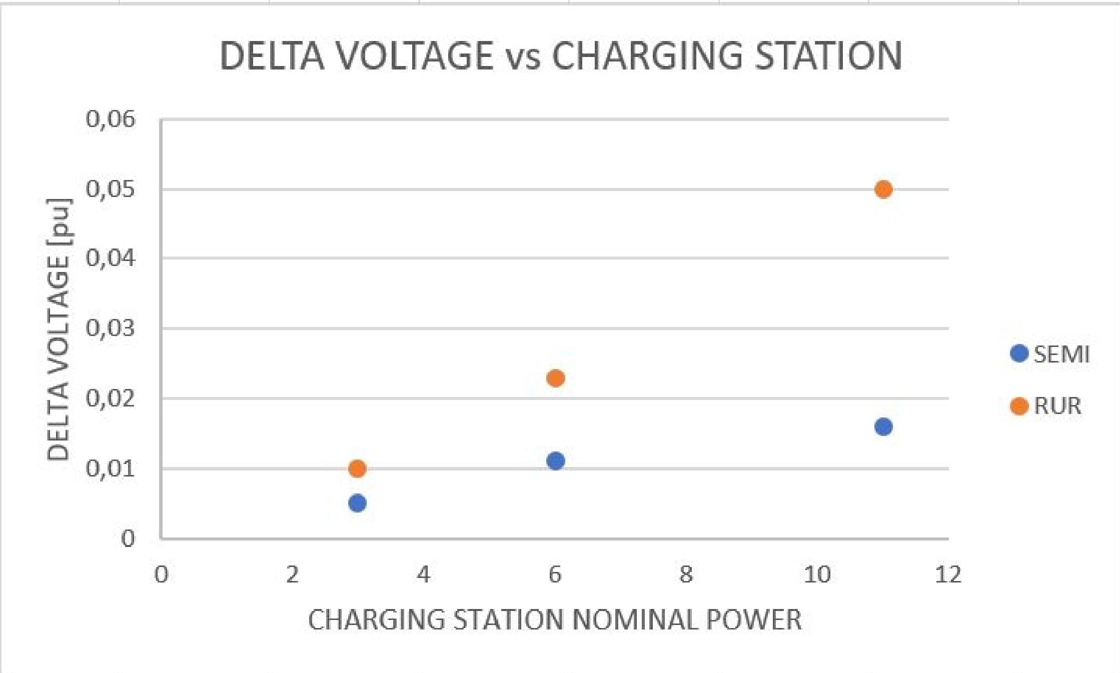


Figure 5.37: Maximum voltage drop on the networks vs charging station (Population=15000 agents).

Chapter 6

Conclusion

The work carried out highlighted the potential of using agent models in an electrical environment. The use of these algorithms for studying loads due to PEVs is particularly interesting. Compared to what has been seen in the literature, the goal was to recreate a solid working structure in different proposed scenarios. The implementation of the *Parametric Analysis* has allowed, in addition to studying particular conditions, to verify the solidity of the tool created.

From the *social* point of view, it is very interesting to observe the correlation between the different layers of the model. This is observed for example by comparing the electrical loads on the network with respect to the map indicating where the agents live and work. The correlation is strong and if the case study is interpreted as a real case, measures should be taken to this effect. In fact, in this case study, is clear that the city center (in general the semi-urban network) is definitely more attractive for the agents of the rural network (among other things electrically weaker). Despite this, it has been observed that peripheral distribution networks are not designed to accommodate a large number of electric vehicles. The results showed that the presence of a few attracting nodes for the agents has already created a considerable increase in the currents in the branches. This depends on the characteristic of the rural network, designed for smaller power flows and therefore realized with smaller section conductors (with higher losses).

A network operator could operate different strategies:

- Address the car-sharing service operator to the electrically more solid network portions. However, reality tells us that the two figures are distinct and there is no reason to collaborate.
- Strengthen the existing electricity grid to compensate for additional load peaks.
- Request the car-sharing service owner to operate on the network as an *active* user. Implementing V2G in fact the benefits would be on both sides. The service operator would be paid by the DSO to help the operational of the network. The distribution system operator can optimize the operating costs of the network by compensating for the peaks in demand at the time of greater charge of vehicles.

The implementation of this model requires an additional layer, placed at the top of the layer scheme. This layer would be the *ECONOMIC LAYER*. In fact, communications between the DSO and the car-sharing service manager would be of an economic nature, with the aim of maximizing the profit for the service provider and improving the network profiles for the DSO.

An economic model would imply the implementation of the so-called *day-ahead market*. The service manager buys the planned energy and its job is to dispatch it to the various stations the following day. Failure in excess or in default leads to an economic loss. In the proposed model it is interesting to observe how the rural network is weaker than the technical limits despite the presence of fewer vehicles. A network operator, faced with these data, could evaluate to strengthen some branches because if in a real network there was a particularly attractive node (e.g., a large industry), a portion of the network would be in critical condition. As indeed it has been said, a model with agents does not present certain results but, as in this case, allows us to realize what could be the critical issues to which we are going. In conclusion, the model created is a solid base on which to evolve the studies of electrical distribution networks in the presence of PEVs. Refining the model with the presence of renewable generation, active participation of vehicles, economic policies, would allow to "play"as the DSO. To be able to see concretely how a complex system reacts to the inputs to which it is subject, could in fact highlight what strategies will be implemented in the future.

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