SPATIAL MODELLING TO ALLOCATE LOCATIONS FOR PUBLIC CHARGING STATIONS

Determining the locations of public charging station for the municipality of Eindhoven

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Preface

Hereby I present to you my graduation thesis for the master program Construction Management & Engineering provided by the Eindhoven University of Technology. This thesis is the result of research in the field of electric mobility and more specifically public charging infrastructure. The research is performed in association with HetEnergieBureau which is a consultant agency on sustainability in the fields of energy, mobility and the built environment.

The world of electric mobility is changing rapidly and constantly. For me it was very interesting to learn about these development and to anticipate on the changes within the field of public charging infrastructures. Although I have only been involved with electric mobility for half a year I have witnessed many developments and I have become even more interested.

For introducing me to the world of electric mobility I would like to thank my colleagues at HetEnergieBureau for support and advice. I would especially like to thank Jeroen van Gestel for his guidance and the interesting discussions we had about electric mobility.

From the TU/e I would like to thank Bauke de Vries and Han Qi for their guidance. During my graduation they have provided me with insights and directions for my research. Many of the meetings with them reaffirmed the complexity of this research and I would like to thank them for their constructive feedback.

Furthermore I would like to thank my family, friends and girlfriend not only for their support during my graduation but also for their support during my entire studies.

Geert Kanters

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PART 1 FRAMEWORK & CONTEXT

Chapter 1 Introduction

1.1 Context

The development of electric mobility and electric vehicles has increased significantly over the last couple of years. Global awareness about the impact of human activities on the environment has become much greater over the past decades. Resources such as fossil fuels are getting more scarce and pollution, especially in densely populated areas, is threatening the quality of life. Global agreements on reducing emissions have been made, targets have been set and actions have been taken to achieve environmental goals. In order to continue the process towards a cleaner and more sustainable environment, innovation is needed. Urban areas can still improve significantly to become more sustainable. New developments in the field of electric mobility will contribute to reach sustainability goals. The use of electric vehicles in urban areas will decrease carbon emissions, increase the air quality and contribute to the overall quality of life within urban areas.

Governments acknowledge the importance of electric mobility and have developed policies to meet low emission objectives by stimulating the use of electric vehicles. The use of electric vehicles is regarded as an opportunity to decrease the consumption of fossil fuels and therefore to decrease carbon dioxide emissions.

However, the use electric vehicles largely depends on a supporting charging infrastructure for electric vehicles. Electric vehicles and a charging infrastructure are interdependent; the development of electric vehicle usage requires a supporting infrastructure and installing a charging infrastructure is only useful when a certain level of electric vehicle usage is reached. This interdependence results in a great challenge for the development of electric mobility. It is assumed that in order to disrupt this dependency circle a supportive charging infrastructure must be in place prior to the introduction of a new technology (Sovacool & Hirsh, 2009). The introduction of electric vehicles has to deal with a phenomenon called technological lock-in. Lock-in occurs when an existing and stabilised systems hamper the development of new technologies. The lock in of fossil fuels is called carbon lock-in and this too is a great challenge for the development of electric mobility (Uhruh, 2000).

1.2 Research approach

In this paragraph the approach for this research will be described. First the problem will be defined for this research, followed by the main research question and sub questions. Finally the objective of this research will be clarified.

1.2.1 Problem definition

As mentioned before it is desirable to develop a supporting infrastructure in order to stimulate the use of electric vehicles. However, the development of a public infrastructure is hampered because currently there is no profitable business case for public charging stations. Most of the developments for a public charging infrastructure are generally initiated as pilot projects by governments, network operators and research institutes. It is expected that after 2015 a profitable business plan for public charging station can be developed (PRC, 2013) and that the market for public charging services will grow from a developing market to a mature market (Innopay, 2011).

A growing market for public charging services presents new challenges. This research focuses on the spatial challenges that a growing market for public charging services entails. Currently little attention has been paid to determine strategic locations for public charging stations. In most cases public charging stations are placed on request. For local governments it is important to carefully determine the locations for public charging stations because they will be located in public areas which are in most cases municipal grounds. On the one hand municipalities want to facilitate electric vehicle drivers but on the other hand municipalities want to avoid financial costs and unnecessary pollution of public spaces. These principles will have to be balanced. Especially municipalities with urban areas are confronted with this problem because public spaces and parking spaces are more scarce and require an amount of flexibility. Furthermore, the demand for public charging stations in urban areas will be high, because the majority of electric vehicle drivers in cities will not be able to recharge their vehicles on private grounds.

The problem definition for this research is phrased as: *"An integrated approach for allocating locations for public charging stations is lacking"*. The owner of this problem is for the majority of cases a local government or municipality and the problem is most relevant to urban areas.

1.2.2 Research questions

The main question for this research is: *What model can be used to allocate locations for public charging stations?*

Before the main research question can be answered several sub questions need to be answered first. The sub-questions are:

1. What is the current situation of electric mobility in general and in The Netherlands? What developments have occurred and which stakeholders are involved?
2. Which drivers in the field of charging stations are essential for future developments of charging infrastructures?
3. Which objectives can be identified for public charging stations to be functional? And which variables are linked with these objectives?
4. Which approaches can be used to create a location allocation model and how can they be combined?
5. How can a case study and scenarios be used to apply a location allocation model to the real world?

The sub questions will be used throughout the report because the chapters will refer to the sub questions. In chapter 9 the main research question will be answered.

1.2.3 Objectives

The objective of this research is to create a location allocation model for public charging stations. The municipality of Eindhoven will be used as a case study to apply the model to the real world. The objective is to create solutions for the location problem of public charging stations in the municipality of Eindhoven. The overall objective of this research is to advise other municipalities on the locations of public charging stations as well.

1.2.4. Research boundaries

This research will mainly focus on the developments of electric mobility within The Netherlands until the year 2020. For the case study the municipality of Eindhoven is used. Furthermore in this research will only consider electric vehicles which are capable of recharging at stations by using cables and plugs.

1.3 Research model

In figure 1 the research model is illustrated. The research model can be divided in a theoretical part which is desk research and conditions and a rather practical part which is design and scenario analysis.

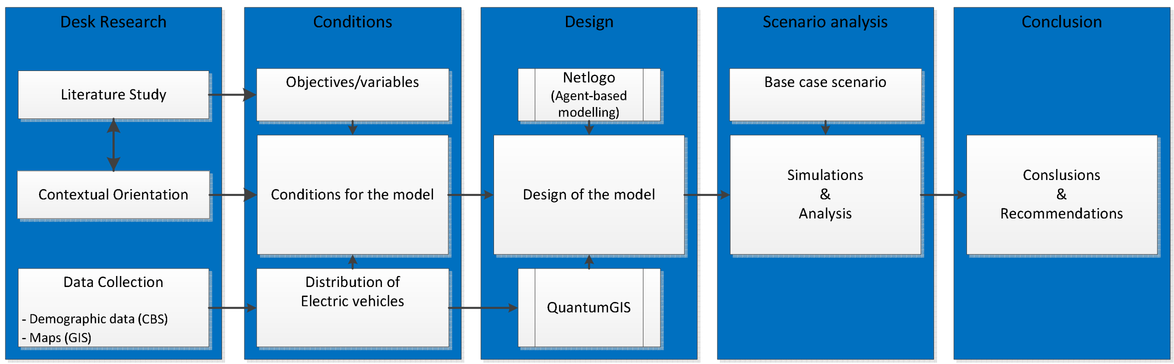

Figure 1 Research model

1. The first step of the model will be desk research which involves a literature study, contextual orientation and the collection of data. The literature study is mainly about agent based modelling, multi-objective optimisation, scenario analysis, location problems and GIS. The contextual orientation will be used to get experienced in the field of charging station and every other relevant aspect of electric mobility.
2. The conditions for the model will be based on both the contextual orientation and the literature study. The distribution of electric vehicles also influences the conditions of the model.
3. To design the model the software programs QuantumGIS and Netlogo will be used. QuantumGIS is used to create the environment with a distribution of vehicles and Netlogo is used to write the codes and to run simulations with.
4. A base case scenario will be created for the scenario analysis to find a solution for the location problem.
5. Finally conclusions will be drawn based on the solutions and recommendations will be made.

1.4 Research methods

For this research several research methods are used which are also shown in the research model. The used research methods are multi-objective optimisation, agent based modelling and GIS.

Agent-based modelling is a simulation technique for modelling complex systems. An agent-based model generally has three elements; a set of agents with attributes and behaviours, a set of relationships and methods of interaction and the agents' environment (Macal, 2010).

The systems are modelled as a collection entities called agents. The main benefits of agent-based modelling is that is captures emergent phenomena, provides a natural description of a system and it is flexible (Bonabeau, 2002).

Geographic information systems (GIS) are used to gather, analyse, modify, manage and present all types of spatial information. GIS is an operational and supporting information system where data can be related to a specific location or area. Combining data with geographic information such as maps, results in numerous forms of output. With GIS many products can be created such as maps, charts, tables and graphs. GIS is commonly used in planning, analysis of traffic, transport, environment, safety, earth sciences and many more applications.

With multi objective optimisation a trade-off between divergent objectives exists which results in a number of solutions. If one solution is better in terms of one objective, it comes only from a sacrifice off other objectives because the objectives are not independent (Deb, 2005). The aim of multi objective optimisation is not to solve a single objective or to find an optimal solution corresponding to each objective function (Deb, 2005).

Chapter 2 Contextual orientation

In this chapter general aspects and characteristics of electric mobility will be described. The first paragraph will describe the developments of electric mobility in general followed by an introduction of electric vehicles. In the third paragraph electric mobility in The Netherlands will be explained. This paragraph will also describe the objectives for electric mobility in The Netherlands as well as important stakeholders.

Together with chapter 1 this chapter will provide an introduction of this report and at the same time it will provide an answer to the first sub question of this research. The first sub question as mentioned in paragraph 1.2.2 is: what is the current situation of electric mobility in general and in The Netherlands? What developments have occurred and which stakeholders are involved?

2.1 Electric mobility in general

Electric mobility refers to the use of electric vehicles which are driven by electricity. Although electric mobility seems a brand new development which fits in our pursuit of achieving sustainability, it is not a new development at all. By the end of the 19th century electric vehicles were very common and they played an important role in the upcoming car industry. Because combustion engines were still under development, electric vehicles had a number of important advantages over vehicles with a combustion engine; easy to start, easy to operate, no fumes, no noise and they used very simple technologies. The disadvantage of electric vehicles was and still is its limited range (Wouters, 2013).

Over the last couple of years again, the development of electric mobility is growing rapidly. This time the driver for the development of electric mobility is not merely technology but also the global awareness of the impact of human activities on the environment. Important drivers among others, are political and economic developments. Electric mobility can be stimulated by governments through financial and fiscal incentives such as subsidies and tax exemption but also by public investments (JRC, 2010). Economic factors such as energy prices for both fossil fuels and electricity can positively influence the development of electric mobility. Economies of scale will reduce prices for electric vehicles and batteries which can stimulates the development of electric mobility as well.

Although the global market for electric vehicles is growing rapidly it is no guarantee for success. The development of electric mobility is facing the very mature market of conventional car manufacturers. Fortunately, existing car manufacturers are increasingly involved in the developments of electric mobility. Every year more electric vehicles are introduced to the market.

2.2 Electric Vehicles

Future developments of electric vehicles will be very important for the growth of electric mobility. Existing car manufacturers have an essential role in these developments because for the most part, they will eventually determine which electric vehicles and which technologies will enter the market. The performances and costs of batteries for electric vehicles is perceived as one of the greatest barriers for the development of electric mobility (JRC, 2010). In this paragraph the concept of electric vehicles will be introduce briefly.

2.2.1 EV & PHEV

A distinction is made between full electric vehicles (FEV or BEV) and hybrid electric vehicles (HEV) . Full electric vehicles such as the Nissan Leaf and the Tesla Model S are solely driven by batteries. Hybrid electric vehicles on the other hand are driven by both a combustion engine and batteries. A distinction is made between hybrids with a direct combustion engine and hybrids with a generator which charges the batteries which in turn drives the car. Plug-in hybrid electric vehicles (PHEV) are hybrids which can be plugged in for recharging. An example of an HEV is the Toyota Prius and an example of a PHEV is the Opel Ampera or Toyota Prius plug-in. Since this report focuses on a charging infrastructure for electric vehicles it is obvious that only full electric vehicles and plug-in hybrid electric vehicles are taken into consideration. Appendix A shows an illustration of different electric vehicles.

This research only considers rechargeable electric vehicles such as full electric vehicles and plug-in hybrid vehicles.

The sales of plug-in hybrid electric vehicles are expected to grow rapidly while the sales of full electric vehicles will increase moderately (LCA Works, 2012). Appendix B shows a scenario of electric vehicle sales until 2050. The graph describes a plausible future where the global sales of both plug-in and full electric vehicles outrun the sales of conventional combustion engine vehicles between 2030 and 2035 (LCA Works, 2012).

2.2.2 Batteries

The development of batteries is considered to have one of the biggest impacts on the development of electric mobility. Currently Li-ion batteries is the technology of choice for all new electric vehicles being commercialised (LCA Works, 2012). Today's research is focusing on advanced materials that can significantly improve the energy density of Li-ion batteries (LCA Works, 2012). The batteries of a Nissan Leaf for example have an energy density of 120Wh/kg and a capacity of 24 kWh. It is expected that energy densities will increase up to 300 or even more by 2020 (LCA Works, 2012). For (potential) electric vehicle drivers, range is the most important criterion when it comes to batteries and performance. The range of a battery does not only depend on its power density but also on the weight of the battery itself, its life expectancy, the weight of the car, charging patterns, driving behaviour and weather circumstances. Currently the average range of full electric vehicles varies between 80 and 300 kilometres. The Nissan Leaf for example has a range of approximately 150 kilometres while the Tesla Model S can drive up to 300 kilometres with a fully loaded 60 kWh battery. It is expected that by 2020 the average range will be up to 250 kilometres or even more (JRC, 2010). It is assumed that an average efficiency of 0,15 kWh/km and lower will be reached over the next years (IEA, 2011).

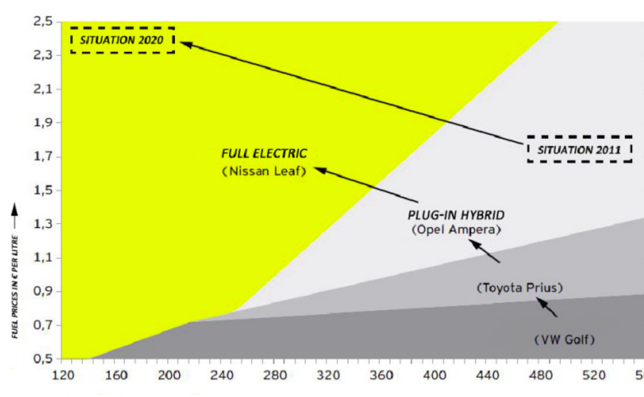

Figure 2 Energy and power densities of batteries (LCA Works, 2012)

Another important factor for the development of electric mobility besides energy density of batteries are the costs of batteries per kWh. Fossil fuel prices and battery costs per kWh will influence the attractiveness of electric vehicles. Figure 2 shows the competitiveness with conventional combustion engine vehicles. The interaction between battery and fuel costs will eventually determine the size of the market for electric vehicles (McKinsey, 2012).

2.3 Electric mobility in The Netherlands

The development of electric mobility has received a lot of attention in the Netherlands. The E-Laad foundation, a cooperation of Dutch network operators, had the objective to realise 10.000 public charging stations. However, because of a limited budget and interference by the national governance, E-Laad managed to realise approximately 2.500 charging stations until now. The reason for interference by the national government was to stimulate competition and innovation. E-Laad has announced that new requests for public charging stations are no longer accepted. There has been a call for tenders for the remaining 600 requests which were already approved by E-Laad. The E-Laad foundation now challenges organisations to formalise a market model which encourages competition among operators, service providers and other commercial parties. Competition is important because it will stimulate innovation and it will result in payable services which can compete with private charging points.

The sales of electric vehicles is a good indicator for the development of electric mobility. In figure 3 the sales of electric vehicles in The Netherlands is indicated. There is a clear difference between the sales of plug-in hybrid electric vehicles and full electric vehicles. It is assumed that the sales of plug-in hybrid electric vehicles will grow rapidly over the next years. Plug-in hybrid electric vehicles are considered as a transition from combustion engines to full electric vehicles. The national government has set targets for the numbers of electric vehicles in the future which are shown in table 1. The growth of electric vehicles sales as indicated in figure 3 reveals that the target for 2015 is plausible. For 2020 the target is 200.000 electric vehicles on the road. In this research the target for 2020 will be used as a guideline for the case study.

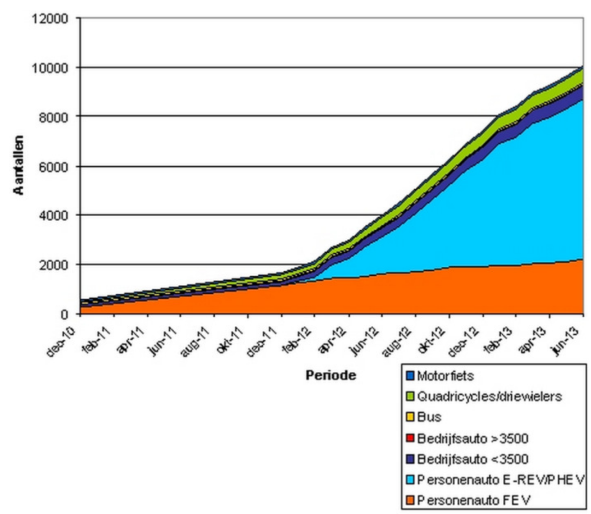

Figure 3 Sales electric vehicles The Netherlands (AgentschapNL, 2013)

Year	Target electric vehicles on the road
2015	15.000 - 20.000
2020	200.000
2025	1.000.000

Table 1 Targets electric vehicles The Netherlands (AgentschapNL, 2013)

The Dutch government aims at 200.000 electric vehicles on the road in 2020

2.4 Stakeholders

Besides E-laad there are many other stakeholders involved in the development of electric mobility in The Netherland such as network operators, utility companies, local and national governments, car manufacturers, fleet owners and interest groups. An example of stakeholder is illustrated in appendix C. There are also a lot of new entrants such as: Formule E-team, The New Motion, EVBox, Greenflux, eViolin, FastNed, Better Place and many others. Formule E-Team is a cooperation of governments, institutes and companies to stimulate the development of electric vehicles through the development of strategies. The Formule E-Team Task Force is a division of Formule E-team which mainly focuses the implementation of electric mobility by applying the developed strategies. The New Motion is a consortium of mainly car manufacturers and network operators and is a typical new entrant. The New Motion functions both as owner and service provider for public and private charging facilities. Eviolin is an association of charging station operators and service providers. EV-Box is also a new entrant, they produce charging stations for public and private spaces and their mission is to contribute to the deployment of a charging infrastructure. FastNed is a company which focuses on the realisation of a national fast charging network consisting of about 200 fast charging stations along Dutch highways. Besides these organisations there are many more companies and organisations involved in the development of electric mobility in The Netherlands.

The Formule E-team has commissioned the Dutch knowledge platform for infrastructure, traffic, transport and public space (CROW) to develop a directive to support municipalities, provinces and landowners with their choices on the instalment of private, semi-public and public charging stations. These types of stations will be described more detailed in paragraph 3.1.3. The directive also advices on suitable locations, markings, signs, contracts and tenders. The content of the CROW directive will be created by involved stakeholders such as municipalities, charging station operators, network operators and car manufacturers. The directive will be published in the autumn of 2013 (AgentschapNL, 2013).

2.5 Conclusion

Future developments of electric vehicles will be very important for the growth of electric mobility. The performances and costs of batteries for electric vehicles is perceived as one of the greatest barriers for the development of electric mobility.

With electric vehicles a distinction is made between full electric vehicles and hybrid electric vehicles. Plug-in hybrid electric vehicles (PHEV) are hybrids electric vehicles which can be plugged in for recharging. This research will only focus on rechargeable electric vehicles which are full electric vehicles and plug-in hybrid electric vehicles.

In The Netherlands electric mobility is growing steadily and even as a small country The Netherlands has a significant role in the development of electric mobility. Especially on the infrastructure side The Netherlands has developed a reasonable network of charging stations so far. Until now the E-Laad foundation, which is a cooperation of network operators, has realised many public charging stations throughout The Netherlands. However, E-Laad is no longer processing requests for the instalment of public charging stations because of limited budgets and interference by national governments. It is up to commercial parties to continue the deployment of a public charging infrastructure.

PART 2 CHARGING STATIONS & VARIABLES

Chapter 3 The field of charging stations

In this chapter the diversity of charging stations and different applications of charging stations will be elaborated and this chapter will provide an answer to the sub question; which drivers in the field of charging stations are essential for future developments of charging infrastructures? The first paragraph will explain the technical and physical differences among charging stations along with the standards and regulations. Next, the business case of public charging stations will be described, which highlights some of the economic and financial drivers. In the third paragraph electric vehicles will be described followed by the relationship electric vehicles and charging stations.

The analysis of charging stations and the use of charging stations will mainly be focused on current practices in The Netherlands since the model will be used in a Dutch context. For constructing the model it is essential to understand the current and future practices in the field of charging stations. This research will focus on charging stations which recharge electric vehicles by using cables and plugs. Other charging techniques such as battery swapping and inductive charging will not be the focus of this report because these techniques are used on a much smaller scale until now.

3.1 Charging stations

The sole purpose of a (re)charging station is obviously to replenish batteries of electric vehicles. Although this process seems to be fairly simple, there is much more to it. There are, for instance, different kinds of charging stations in terms of capacity and accessibility and the application of charging stations requires a complete charging infrastructure with its own challenges such as the impact on the energy distribution grid. The complications on this impact are considered to be out of the scope of this report.

3.1.1 Standards & Technology

To stimulate electric vehicle usage it is essential to ensure that different kinds of charging stations are compatible with different kinds of electric vehicles. Therefore several standards have been developed concerning the performance, suitability and safety of charging stations.

The International Electrotechnical Commission (IEC) describes four modes of charging stations in the IEC 61951 standard. These modes are distinguished by the maximum charging power and the communications with the vehicle. Mode 2, 3 and 4 require communication between the vehicles and the charging station. A mode 4 charging station is completely different because it uses a direct current (DC) instead of an alternating current (AC). For all AC charging stations electric vehicles require an on-board charger (converter) because a battery can only be charged with DC current. A mode 4 charging station has a build in charger which makes it considerably more expansive than other charging stations.

Besides these four modes of charging stations there are also three types of plugs described by the IEC 62196 standard. Type 1 is based on the US SAE J1772 standard and many electric vehicles such as the Nissan Leaf and Opel Ampera have a type 1 inlet. Type 2 is the European standard and also known as the Mennekes plug. For instance the Renault Zoe and the Volvo

V60 PiH are equipped with this inlet. Finally there is a type 3 plug which is mostly used for charging stations in France and Italy. Besides these three types of plugs there are also the standard household plug (Schuko) and the CHAdeMO plug for fast charging. In appendix D an illustration of the three types of plugs is given. In table 2 an overview of charging stations with different modes and plug configurations is given. It clearly indicates that although there are standards about different modes of charging stations and types of plugs, there are many possible combinations which result in a considerable number of options to choose from for both manufacturer as user.

Current	Charging Station	Mode	Single-phase	Three-phase	Plug Configuration
	Slow charging	Mode 1	max. 16A 3,7 kW	max. 16A 11,0 kW	Schuko (standard household plug)
AC	Semi-fast charging	Mode 2	max. 32A 7,4 kW	max. 32A 22,0 kW	Type 1, 2 or 3
	Fast charging	Mode 3	max. 64A 14,7 kW	max. 64A 44,0 kW	Type 1, 2 or 3
DC	Fast charging	Mode 4	max. 400A 1000V (>50 kW)		TEPCO (CHAdeMo)

Table 2 Charging station modes

Eventually the capacity of a charging station is determined by its power in kW and the number of plugs. The number of plugs on a charging station can vary from one to four plugs. A charging station can have four plugs for example when it is placed in the middle of four parking spaces.

3.1.2 Regulations

Standards play a key role in the development and deployment of technology in society, providing an indispensable basis for widespread market penetration and customer convenience (Eurelectric, 2009). To further stimulate electric vehicle usage and to increase the deployment of charging stations, standards for both hardware and software are essential. Common standards will help to reduce costs and to create economies of scale. The main purpose of standards is to ensure that electric vehicle drivers can safely and conveniently enjoy the use of both electric vehicle and charging station. In other words it increases user acceptance (ACEA, 2012).

In 2012 the European Automobile Manufacturers' Association (ACEA), European Association of Automotive Suppliers (CLEPA) and Eurelectric jointly agreed on the need for a single harmonised plug system for the recharging of electric vehicles on both the vehicle and the infrastructure sides. For electric vehicle inlets the ACEA does not describe any restrictions since many manufacturers already apply different types on the market. On the infrastructure side however the ACEA recommends a type 2 mode 3 plug for public charging. From 2017 onwards the ACEA recommends a type 2 mode 3 inlet for electric vehicles as well. For fast charging the ACEA recommends fixed cables with a type 2 or combo 2 connector. A combo 2 connector is a type 2 plug with additional DC wires that fits DC charging stations.

In The Netherlands most of the charging stations are equipped with a type 2 mode 3 plug. All the charging stations installed by E-Laad have a type 2 mode 3 plug and use the Open Charge Point Protocol (OCPP). OCPP is a communication protocol which enables electric vehicles to communicate with a central system. The protocol is initiated by E-Laad and allows charging stations and central systems from different vendors to easily communicate with each other. The protocol is already used by more than 400 members in over 35 countries (OCCP, 2013). For fast charging the CHAdeMo plug is mostly used in The Netherlands.

Standardisation of charging stations will decrease costs and increase user acceptance

3.1.3 Accessibility

Charging stations are not only distinguished by its mode and plug type but also by its accessibility. The accessibility of charging stations is one of the key factors for increasing electric vehicle usage because it deals with range anxiety. Figure 4 shows the different kinds of charging stations in terms of accessibility.

The accessibility of a charging station depends on whether the parking space and charging station are located on public or private grounds. First of all there are private charging facilities which are located on private grounds and only accessible for the owner or with permission of the owner. Examples are residences or offices with a private parking area. In urban areas between 70% and 90% of car owners are not able to park and charge at privately owned spaces (JRC, 2010). Secondly, there are charging facilities which are located in public spaces where both station and parking space are on public grounds. These stations are known as public charging stations.

However, there are variations on both private and public charging stations. Some charging stations, for instance (paid) parking garages, are privately owned and on private grounds but they are publicly accessible. Another variation is called extended private charging stations (verlengd privaat laadpunt). The station is privately owned but the parking lot is in public space. The charging station can be located either on private or public grounds as indicated in figure 3. An extended private charging station allows electric vehicle owners without a private parking space to charge at home. The charging station might also be used by third parties against a compensation for the owner. The advantages of an extended private charging station compared to a public charging station are lower initial investment costs and lower operating costs.

The possibilities of implementing extended private charging station are currently investigated in The Netherlands. Especially local government have a crucial role in adapting their policies to allow the use of extended private charging stations. Legal objections are not an issue because the legal articles for parking and parking spaces are sufficient (Movares, 2013).

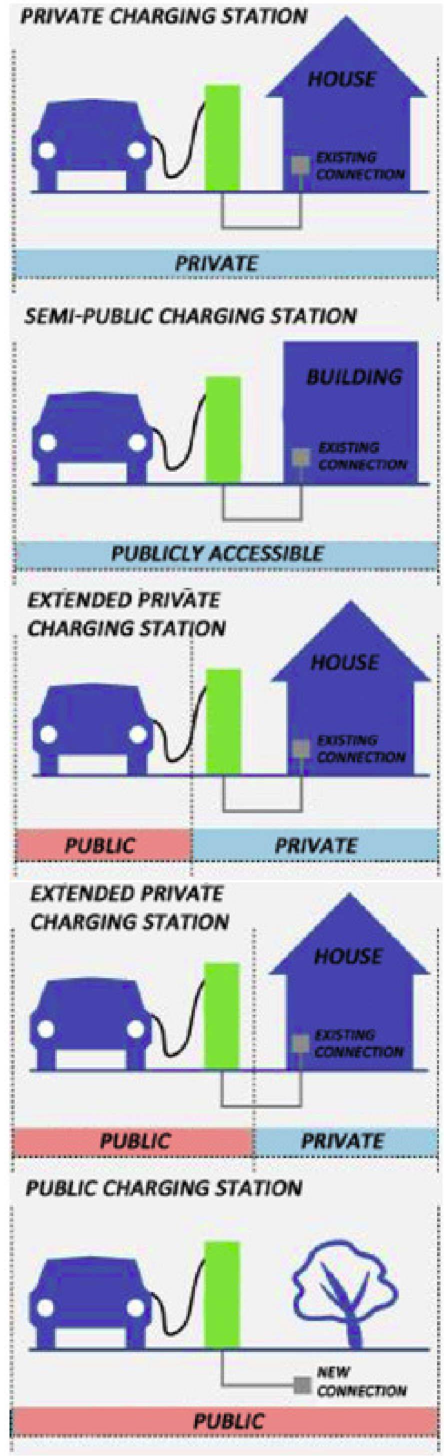

Figure 4 Accessibility of charging stations (AgentschapNL, 2013)

This research will focus on publicly accessible charging stations which are: public charging stations, extended private charging stations and semi-public charging stations.

3.1.4 Charging Tree

In 2013 the Dutch Ministry of Economic Affairs and the Taskforce Formule E-Team have jointly developed a guideline which is also known as "charging tree" (Ladder van Laden) which is shown in figure 5. This charging tree is a national guideline for the employment of a charging infrastructure. The main principles behind the charging tree are realising charging station cost-efficiently, ensure locations of charging stations on both public and private grounds and to ensure that the charging infrastructure fits to the needs of different target groups (E-Mobility, 2013). The charging tree prioritises the previously described accessibilities of charging stations. This way the effectiveness and (cost) efficiency of charging stations will be increased. Private charging stations have the highest priority because charging at home on private grounds is most favourable for both electric vehicle drivers as (local) governments. On the contrary, public charging stations have the lowest priority because currently there is no profitable business plan for public charging stations. Nevertheless publicly accessible charging stations are essential for future developments of electric mobility and therefore extended private charging stations and semi-public charging stations bridge the gap between public and private charging stations. Semi-public and extended private charging stations are more likely to be profitable because they employ already existing connections to the power grid and they are more suitable to create a profitable business case with.

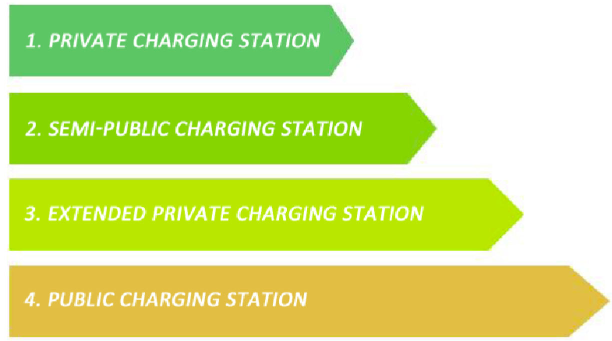

Figure 5 Charging Tree (Formule E-Team, 2013)

3.2 Business case public charging stations

As mentioned before, public charging stations are more expansive in comparison with private charging stations and the current business case for operating a public charging station has a financial gap. This paragraph describes the initial investment costs and the annual operating costs and revenues for public charging stations.

3.2.1 Initial investment costs

The initial investment costs of a typical E-Laad public charging station, comprises of costs for a leasehold estate, connection to the grid, placement and coordination, hardware and application processing. Costs for a leasehold estate are cost for a temporary right to install a charging station in public space. Table 3 provides an overview of the total investment costs needed for a public charging stations. The table clearly indicates that the costs for hardware contributes most to the total initial investment (PRC, 2013).

Initial investment costs	€
Leasehold estate	500
Connection	1000
Placement	1100
Hardware	3200
Application processing	500
Total	**6300**

Table 3 Initial investment 11 kW public charging station (PRC, 2013)

3.2.2 Annual operating costs and revenue

The annual costs consist largely of depreciation, energy purchase, operating, network and management & maintenance costs. The depreciation expenses plus interest are derived from the initial investment and based on a 3 year operating period with an interest rate of 5%. Network costs are charged by network operators for constructing, managing and maintaining the electric energy network. Table 4 shows the annual profit and loss statement. It is immediately apparent that the revenue based on a the sales of 3000 kWh per year is far too low to cover the annual operating costs; the table indicates a substantial annual loss for every public charging station (PRC, 2013).

Annual Profit and Loss Statement	Expenses (€)	Revenue (€)
Depreciation plus interest	2260	
Operating	300	
Management & maintenance	500	
Network	770	
Purchase (energy)	540	
Sales (energy)		690
Loss		3680
Total	**4370**	**4370**

Table 4 Profit and loss statement 11 kW public charging station (PRC, 2013)

Currently, public charging stations have an annual financial gap of approximately € 3.500,- over an operating period of 3 years.

3.2.3 Improvement business case

There are several options to improve the above described business case for public charging station. The most important condition is that governments actively facilitate operators by reducing costs for leaseholds and permits. Legal aspects such as the Electricity Act must be altered. These new conditions will reduce the initial investment costs significantly (PRC, 2013). The network operators also play a crucial role in creating a profitable business case by reducing costs for the connections to the grid. Eventually economies of scale and more sales of energy will also contribute to the viability of the business case.

3.3 Relationship electric vehicle usage and charging stations

Previously, charging stations with different types, capacities, modes and accessibilities have been described as well as the different electric vehicles and limitations of current electric vehicles. In this paragraph specific charging stations will be matched with different charging locations, target groups and different usage patterns. Table 2 in paragraph 3.1.1 will be of use to identify the indicated charging stations.

3.4.1 Charging at home

Being able to charge an electric vehicle at home is essential for electric vehicle owners. Electric vehicle owners have to be able to rely on charging facilities within a limited distance from their homes. Especially during the evening and at night when the vehicle is parked at home and idle there is plenty of time to fully recharge a vehicle. Since the majority of car travel occurs during the day there is an abundance of time left at night to charge a vehicle (SCP, 2011). As a result slow chargers are very suitable for charging in residential areas. Not only are they affordable but for private usage, slow chargers are also easy to install and they can easily be connected to the existing power supplies. When public charging stations in residential areas have to be shared by multiple electric vehicle owners it might be desirable to use a semi-fast charger because the charging time per vehicle will be less and thus more owners can use the facility.

3.4.2 Charging at work

Another obvious charging location is at workplaces. Being able to charge at work is essential when commuting trips are longer than half the range of the vehicle. However, in The Netherlands the average distance between residence and work is approximately 22 kilometres and the average car trip is 17 kilometres (AgentschapNL, 2013). Being able to charge at work will also overcome range anxiety and it is a key condition to promote electric vehicles (JRC, 2010). Depending on working hours and potential vehicle usage during working hours, the available time for charging at work is abundant meaning that a slow charger will be sufficient in most cases. Semi-fast chargers might be desirable for visitors or other short stays at workplaces.

3.4.3 Commuting

One of the most important target groups for the use of electric vehicles are commuters. Commuters drive relatively short distances per day and their charging locations are known upfront; at home and at work (AgentschapNL, 2013). The predictability of driving patterns of commuters is one of the reasons for this target group to be suitable for the use of electric vehicles. Electric mobility requires more planning and the regular travels of commuters are planned well ahead. Besides the advantages of fixed distances and locations there are also financial advantages for employers and car leasing companies. Car leasing companies can develop a new competitive market strategies by offering a total solution for commercial electric vehicle fleets. This implies a shift from selling merely driven kilometres to selling mobility services such as charging infrastructures. Recently car leasing companies have started to incorporate electric vehicles into their fleets but there are still enough challenges to address (AgentschapNL, 2012).

3.4.4 Non- commuting

Non-commuting trips can vary from short trips for daily shopping to long distance trips for holidays. Either way charging facilities are necessary to make these trips. Most of the non-commuting short trips are visits to shopping areas, recreational areas, restaurants, friends & family or other (public) services. In most cases people tend to stay approximately 2 hours which limits the amount of time for charging. Mode 2 semi-fast or mode 3 and 4 fast chargers are in most cases sufficient to recharge the vehicle within the limited time frame and should be placed at location with a high visiting rate such as shopping centres. For long distance travels to for example holiday destinations fast chargers are essential and useful locations might be along highways or any other places with high traffic flows. Table 5 provides an overview of the charging modes and applications.

	Mode 1	Mode 2	Mode 3	Mode 4
	AC slow charging	AC semi-fast charging	AC fast charging	DC fast charging
Compatible accessibility	Private	Public	Public	Public
Applicable	Residential areas	Residential areas	Shopping centres	Shopping centres
locations	Working areas/offices	Working areas/offices	(Public) Services	(Public) Services
	(Long term) Public parking	Public parking	High density traffic flows	High density traffic flows
	Park & ride facilities	Shopping centres	Existing gas stations	Existing gas stations

Table 5 Applications of charging station modes

3.4.5 Limitations

Both charging stations and electric vehicles come along with certain limitations, which have to be dealt with now and in the future. For charging an electric vehicle the power of a charging station does not solely determine the charging speed. The speed of recharging is determined by the capacities of the charging station *and* the capabilities of the vehicle itself. For electric vehicles the on-board charger determines the charging power of the vehicle. A fast charging station might stimulate electric vehicle usage but if a car is only capable of charging at 3,7 kW due to its on-board charger than a fast charging station has no advantage over a slow charging station.

The (re)charging speed is determined by the capabilities of both charging station *and* electric vehicle.

Currently most electric vehicles have an on-board charger with a maximum power of 3,7 kW. The Tesla Model S has a 10 kW on-board single charger and the Renault Zoe even has a 43 kW on-board charger. It is expected that over the next years the power of on-board chargers for AC charging will increase. If electric vehicles enable AC fast charging than AC fast charging station will have a great advantage over DC fast charging station because they are much more inexpensive.

Charging station themselves also have limitations regarding efficiency in terms of utilisation. Especially for public charging stations it is very common that a station is occupied while it is not charging an electric vehicle. Currently, electric vehicle drivers have no incentive to remove their vehicle after it has been fully charged. As a result drivers only remove the vehicle when they are leaving with their vehicles meaning that in the meantime the station is unnecessarily occupied which drastically decreases the efficiency of a station. Communications between public charging stations combined with financial incentives might encourage drivers to use charging stations more efficiently.

Among others, current utilisation patterns of public charging stations cause inefficiency.

3.4 Conclusion

In this chapter is has become clear that there is a wide variety of charging stations and applications of charging stations. Besides recognising all modes and types of charging stations it is most important to acknowledge the different applications of charging stations and usage patterns. Eventually it is the utilisation of public charging stations which will stimulate electric mobility.

Several essential drivers for the future development of public charging stations can now be identified. The first essential driver is the charging capacity. Fast charging stations will stimulate electric mobility, but the charging speed depends on both the charging capacity of a station and on the charging capacity of an electric vehicle. The charging capacity is also closely related to the utilisation pattern of a public charging station which influences the efficiency. Secondly, standardisations and regulations are crucial for the development of a well-functioning charging infrastructure. Standardisations increase mental comfort and stimulate user acceptance An important economic driver is the profitability of public charging stations. Currently public charging stations are not feasible which hampers the development of a charging infrastructure. Matching electric vehicle usage patterns with types of charging stations will also stimulate the future development of a charging infrastructure. The charging tree (Ladder van Laden) presented by the Dutch Ministry of Economic Affairs and the Taskforce Formule E-Team is a guideline for the implementation of a charging infrastructure. Although these drivers are considered to be the essential drivers for this research, in reality there are most likely even more drivers for the future development of charging stations.

Chapter 4 Objectives & variables

Before any location allocation model can be constructed the objectives of a charging station in relation with its direct environment has to be described. This chapter will focus on how the varieties of charging stations as described earlier, will influence the behaviour of the model. As mentioned in chapter 1, the aim of this research is to create a location allocation model for public charging stations. Allocating a location for a station depends on the interactions between a charging station and its direct surroundings. The location of a charging station could for instance be influenced by the number of electric vehicles in its surrounding. In order to understand and apply these interactions, objectives for the allocation of charging stations have to be formulated.

This chapter will provide an answer to the sub questions; which objectives can be identified for public charging stations to be functional? And which variables are linked with these objectives? The first paragraph will elaborate on multi objective optimisation to explain the use of objectives. The second and third paragraphs will describe the objectives with all related variables and constraints.

4.1 Multi objective optimisation

The model is characterised as a multiple criteria decision making model in which a set of variables is considered and values are used to decide whether a location meets the objectives. Since the location of a charging station has to represent an optimum for the set of variables, multi objective optimisation is used. Multi objective optimisation is able to deal with more than one objective function. Within multi objective optimisation a trade-off between divergent objectives exists which results in a number of solutions. If one solution is better in terms of one objective, it comes only from a sacrifice off other objectives because the objectives are not independent (Deb, 2005). The aim of multi objective optimisation is not to solve a single objective or to find an optimal solution corresponding to each objective function (Deb, 2005). The aim is to find an optimum compromise solution between the objectives. A multi objective optimisation problem considers a set of objective functions, a set of decision variables, and a set of constraints (Marseguerra, 2006). The objectives are derived from the effects that allocation choices have on reliability, availability, maintainability and costs (RAM&S). In this research a subset of two conflicting RAM&S are taken into account; availability and costs. The objectives together with the constraints for the objectives will determine the boundaries for the decision space of the model.

4.2 Objective 1: Availability

The first objective for the location allocation of charging stations is to maximise availability $A(x)$. The availability of a charging station determines among others the usefulness of a station. In other words an unavailable or occupied charging station is useless to electric vehicle drivers in need of recharging. If availability was the only objective the aim of the model would be to achieve maximum availability. The availability of a charging station is determined by demand and supply; high supply and low demand will result in a high availability.

4.2.1 Objective function and variables

The availability of a charging station can be determined by subtracting demand from supply. The objective function for daily availability is:

$$f(x) = A(x) = supply - demand = (o * t * p) - (n * d * e)$$

Where

o: charging output per plug (kW)
t: daily effective charging time per plug (hrs)
p: number of plugs
n: number of electric vehicles using the charging station
d: daily distance travelled per electric vehicle (km)
e: energy consumption per electric vehicle (kWh/km)

The variables mentioned above will be described in more details below. Most of the variables have a direct link with the subjects described in chapter 3.

o: This variable is the charging output or power in kW per plug. In the model different values for the charging output can be set according to the desired or expected charging stations. Paragraph 3.1.1 shows the variety of charging stations in terms of capacity and power. It also shows the range of capacities of charging stations.

t: The supply of a charging station is not only determined by its power but also by its utilisation. The inefficiency of public charging stations caused by utilisation patterns is also mentioned in paragraph 3.4.5. In theory a charging station is capable of charging electric vehicles 24 hours a day. However, it is impossible for a station to recharge electric vehicles every minute of the day because users don't arrive uniformly over a 24-hour day. The practical capacity of a station will be significantly less than the theoretical throughput of the station (Daskin, 1995). Computing practical capacities requires knowledge of queuing theories in conjunction with and understanding of customer behaviour (Daskin, 1995). Incorporate queuing components is beyond the scope of this report. The main reason that a station is not charging an electric vehicle is simply because it is unoccupied and available. Secondly, a station might be occupied, meaning that a parked electric vehicle is connected to the station, but the station is not actually charging because the vehicle is already fully charged. Currently, this situation occurs quite often because there is no incentive for electric vehicle drivers to remove their vehicles after is has been fully charged. Especially during working hours, during the evening and at night vehicles occupy a station while it has already been fully charged. This recharging behaviour dramatically decreases the maximum supply and capacity of a charging station. So, the daily effective charging time per plug is an assumption of the maximum effective charging time per plug. In the model the effective charging time is a variable which can be adjusted according to the assumed maximum.

p: The number of plugs or outlets per charging station can vary as mentioned in paragraph 3.1.1 as well. A station can have only one plug or even four plugs. The latter is only possible if the station is situated on the junction of four parking spaces. Charging stations with more than four outlets have to be created as a strip along a line of parking spaces but these are not (yet) commonly used for electric vehicles.

n: The number of electric vehicles using a charging station is determined by the maximum radius or catchment area of a charging station and by the density of electric vehicles within this area. For the model the density of electric vehicles will be determined by a forecast of electric vehicles which will be described in paragraph 5.3. The catchment area of a charging station is determined by the acceptable walking distance from a station to destination. The maximum distance in a straight line is approximately 200 metres which means that the actual walking distance might be even longer. For this research the maximum radius of a public charging station is set at 200 metres.

d: The daily distance travelled per electric vehicle is a variable based on the average distance of an electric vehicle per year.

e: The energy consumption per electric vehicle is mainly determined by the efficiency of the battery but also by driving behaviour and weather circumstances. Driving conditions can reduce the range of a battery significantly. In paragraph 2.2.2 the current and future battery performances are described.

4.2.2 Objective constraint

The constraint for availability is determined by the relation between demand and supply. If demand exceeds supply, a station will be overloaded which decreases the availability dramatically. The limit for the objective space is reached when demand exceeds supply. The constraint $g(x)$ for the availability objective is:

$$g(x) = Demand \leq Supply \quad \text{or} \qquad 1 - \frac{Demand}{Supply} \geq 0$$

In the model this constraint will set the boundary for the availability objective space and thus also a part of the boundaries for the total decision space of the model.

4.3 Objective 2: Profitability

The second objective for the location allocation of a charging station is to maximise profitability. Considering only this objective, it would be desirable if profits maximised. Currently, public charging stations do not have a profitable business case which is discussed more detailed in paragraph 3.2. The profitability of a station depends on several variables such as the initial investment, interest rates, profits per kWh and utilisation. The latter is one of the most important variables because the utilisation almost directly determines the profitability of a charging station. If a station is used intensively, sales will increase and as a result public charging stations will be more likely to be profitable. For a charging station to be profitable the actual daily utilisation has to be higher than the required daily utilisation for profitability. If the daily utilisation is below the required daily utilisation then the charging station will not be profitable or it will not have the desired rate of return on the initial investment. The objective is to reach a certain level of utilisation in order to be profitable and to reach the predetermined rate of return on the initial investment.

4.3.1 Objective function and variables

The profitability of a charging station can be determined by calculating the actual daily utilisation of charging stations. The objective function for the actual daily utilisation $U_a(x)$ is:

$$f(x) = U_a(x) = \frac{\mathrm{n} * \mathrm{d} * \mathrm{e}}{p * o}$$

Where

n: number of electric vehicles using the charging station
d: daily driven distance per electric vehicle (km)
e: energy consumption per electric vehicle (kWh/km)
o: charging output per plug (kW)
p: number of plugs

4.3.2 Objective constraints

In the model this objective will also determine a part of the boundaries of the total decision space. The constraint for profitability is determined by the interaction between the actual daily utilisation of a station and the minimal required utilisation of a station for profitability. The actual daily utilisation has to be higher or equal to the minimal required utilisation for a station to be profitable.

$$U_a(x) \geq U_r(x)$$

The daily required utilisation U_r (hrs) is calculated by dividing the annual desired yield or revenue by the actual yield of a charging station.

$$U_r = \frac{y_d}{y_a}$$

The annual desired yield for a charging station to be profitable is calculated by multiplying the initial investment costs with the annual rate of return and by considering the eventual capital costs.

$$y_d = c_i * (1 + r)^a * \frac{(1 + i)^a * i}{(1 + i)^a - 1}$$

Where

y_d: annual desired yield (€)
c_i: initial capital investment costs (€)
r: annual rate of return
a: amortisation period (years)
i: interest rate of loan

c_i: As mentioned in paragraph 3.2.1 the initial investment costs include for example costs for hardware, connection to the grid and placement (PRC, 2013)

r: The annual rate of return depends on the desired rate of return by the client. If the client is a non-profit organisation (NPO) then the formula only calculates the annual turnover needed to uniformly pay back the initial capital investment costs including interest for loans if financial capital is used.

a: The amortisation period of a charging station is estimated to vary between 6 and 8 years (PRC, 2013). The residential values after the depreciation period is expected to be zero or very close to zero.

i: The interest rate of loan is the interest on borrowed capital.

The actual annual yield is calculated by multiplying the profits per kWh sold with the power of a charging station minus the costs for operations, management & maintenance and network.

$$y_a = \big((y_e - c_e) * o * p * 365\big) - (c_{op} + c_m + c_n)$$

Where
y_a: annual actual yield (€)
y_e: yield for selling electricity (€/kWh)
c_e: costs for purchasing electricity (€/kWh)
o: charging output per plug (kW)
p: number of plugs
c_{op}: annual operating costs (€)
c_m: annual maintenance & management costs (€)
c_n: annual network costs (€)

Most of the variables are already described in paragraphs 4.2 and 5.2.

y_e: The yield or revenue for selling electricity is determined by the selling price of electricity per kWh. This price can be determined by the operator or owner of the charging station. The selling price of electricity has a limit because at a certain point it will no longer be attractive to drive an electric vehicle. If the electricity prices at public charging station are too high people will seek other ways to (unsafely) recharge their vehicles.

c_e: The purchase price will depend on the operators and if they will be regarded as wholesale users.

Inserting all these formulas into one, the final formula for utilisation $U_r(x)$ is:

$$U_r(x) = \frac{c * (1+r)^{t_d} * \dfrac{(1+i)^{t_d} * i}{(1+i)^{t_d} - 1}}{\big((p_s - p_p) * o * p * 365\big) - \big(c_{op} + c_m + c_n\big)}$$

4.4 Conclusion

In this chapter two objectives are used to construct the decision space for the location allocation model. The identified objectives together with the associated variables answer the third sub question in the first chapter. The suitability of a public charging station depends on the interaction with its direct surroundings. The demand within this environment is considered to be one of the most influential factors for determining the location of a charging station.

The first objective is to maximise the availability of a public charging station. The availability depends on the supply of a station and the demand within the direct surrounding of a station. The constraint for this objective is that the demand of a charging station may not exceed its supply because this will result in occupation. The constraint determines the objective space for availability. The second objective is to maximise profitability because currently the exploitation of public charging stations is not profitable. Profitability is directly related to the utilisation of a station simply because intensive usage will increase revenues which in turn will increase profitability. This way too, the interaction between a public charging station and its direct surroundings determines the suitability of a public charging station, because the demand within this environment determines the utilisation of a public charging station. The constraint for this objective is that the actual utilisation from the direct surroundings of a station must be higher or equal to the desired utilisation for profitability. Again the constraint determines the objective space for profitability.

The objectives themselves do not have multiple maxima or minima. Availability has one maximum and this is reached when the effective supply is as high as possible while the demand is as low as possible or zero. For profitability the maximum is reached when the utilisation is as high as possible which is when utilisation is maximised and a station is utilised continuously. The two objectives are divergent, meaning that if one solution is better in terms of one objective, it comes only from a sacrifice off the other objectives (Deb, 2005). The aim is not to find an optimal solution to each objective but to find an optimum compromise solution between the objectives. The two objectives combined, determine the decision space for the location allocation model which is shown in figure 6. The decision space for the model represents a range of options. This means that a location will be allocated when the number of electric vehicles within the catchment area is between 2 and 8. When different values for all variables are used, this range will shift. A decision space is used instead of a single ultimate decision because it results in a more flexible model and the solutions with the model will cover more demand when a decision space is used.

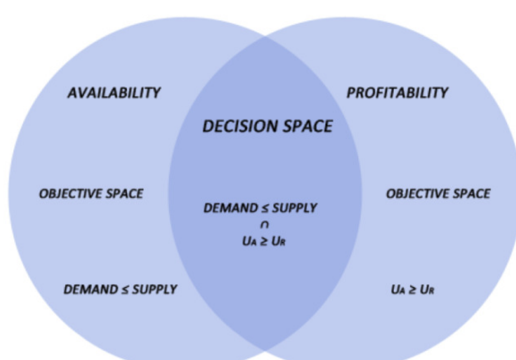

Figure 6 Decision space for the model

PART 3 THE MODEL

Chapter 5 Conditions for the model

In this chapter the conditions for the location allocation model will be described. Over the course of this chapter the used approaches and the combinations of these approaches for creating the model will be clarified, thereby answering sub question 4. The chapter will start with a description of agent-based modelling followed by location problems in general and the location problem for the model. Finally the environment for the model will be described in paragraph 5.3 which will explain in detail how a distribution of electric vehicles is created. Lastly the use of GIS and the program Netlogo will be described. Over the course of this chapter the conditions for the model will be described with more and more detailed.

5.1 Agent-based modelling

Agent-based modelling is a simulation technique for modelling complex systems. An agent-based model generally has three elements; a set of agents with attributes and behaviours, a set of relationships and methods of interaction and the agents' environment (Macal, 2010). Within agent-based modelling systems are modelled as a set of entities called agents. These agents have several characteristics. One of the most important characteristics of agents is that they are self-contained meaning that they are uniquely identifiable individuals. They are also autonomous so they can act on their own within an environment. Although agents make their own decision, they are influenced by information from interacting with other agents. This way agents show adaptive behaviour meaning they can modify their behaviour based on interaction with other agents. Most agents have a goal which allows them to compare outcomes of behaviour and to act on these outcomes. Besides interacting with each other, agents also interact with their environment. The environment in which agents act can be provided by geographic information. In this report the environment will be provided by a geographic information system (GIS) which will be described more detailed in paragraph 5.4.

The main benefits of agent-based modelling is that it captures emergent phenomena, provides a natural description of a system and it is flexible (Bonabeau, 2002). The interactions between agents as described above, result in emergent phenomena. Emergent phenomena can be counterintuitive and agent-based modelling can capture this emergence from the bottom up. Individual behaviour caused by individual rules can result in unexpected collective behaviour. On a relatively simple level, agent-based models can show complex patterns and provide valuable information about the dynamics of the real-world system (Bonabeau, 2002). By providing a natural description of as system, agent-based modelling attempts to model real-world situation closer to reality in comparison with traditional approaches. Traditional approaches use equations to predict and manage the dynamics of a system. Agent-based modelling approaches the behaviour of a system on an individual or micro level. Agent-based modelling can also be referred to as microscopic modelling. Lastly, agent-based modelling is a flexible technique because the model can be altered by having multiple dimensions or by adjusting the complexity of the model.

Agent-based modelling can be applied to a broad range of disciplines. The applications can vary from modelling agent behaviour in stock markets and supply chains to predicting the spread of diseases and modelling immune systems (Macal, 2010).

5.2 Location problems

Before charging stations can be allocated to locations, the facility location problem has to be identified first. This paragraph will describe location problems, the location problem for the model and finally how to solve the location problem for the location allocation model.

5.2.1 Facility location problem

In facility location problems, a facility agent deals with the problem of finding a location that provides services for a spatially distributed demand. Location allocation models, which deal with facility location problems, intend to find a spatial distribution of facilities that maximises or optimises objective functions within one or more constraints (Arentze, 2010). In the literature distinction is made between two different location problems; median problems and covering problems.

Median problems measure the effectiveness of a facility location by determining the average distance by those who visit it. A comparable way to measure the effectiveness of a facility location is to weight the distance between demand and facilities with an associated demand quantity to calculate the total weighted travel distance between demands and facilities (Owen, 1998). A specific form of median problems is the *p*-median problem. A *p*-median problem uses the measure of effectiveness and its objective is to find the locations for a given number of *p* facilities that minimise the total demand-weighted travel distance between demands and facilities. The *p*-centre model considers a comparable problem but instead of minimising an average distance it tries to find a solution that minimises the maximum distance across demand locations (Arentze, 2010). The above described models set out to maximise the accessibility of a facility network by minimising distances.

However, accessibility can also be defined as an acceptable travel distance or time. These problems are known as covering problems because they regard a demand as covered when it can be served within a specific time or distance from a facility. Two main covering problems can be distinguished; set covering problems and maximal covering problems. Set covering problems set out to cover *all* demand points with a minimum number of facilities (Farahani, 2007). Maximal covering problems on the other hand use a given number of *p* facilities to maximise the number of users covered (Arentze, 2010). With maximal covering models the coverage area, which is the radius of the catchment area of the facility, could be set dependent on the size of the facility (Arentze, 2010). Through a transformation of distances the maximal covering problem can be viewed as a special case of the *p*-median problem (Owen, 1998).

5.2.2 Facility location problem for the model

The location problem considered in this research is neither exactly aligned with the definition of a median problem nor with the definition of a covering problem. For the model the maximum walking distance from destination to vehicle or charging station is considered to be a crucial factor determining whether a charging station will be used. If a destination is outside the catchment area of a charging station it is assumed that the destination is not covered and that the station will not be utilised. This problem relates to a covering problem but again the location problem is neither a set covering problem nor a maximal covering problem. The problem for the model is not a set covering problem due to the previously defined objectives because with the objectives not *all* electric vehicles will be covered. If for example a low number of electric vehicles within the catchment area is not within the decision space of both objectives then these electric vehicles will not be covered or serviced by a charging station. The location problem for the model is also not a maximal covering problem because the model does not provide a given number of *p* facilities. The model itself determines the number of facilities based on the decision space of the objectives.

The location problem for the model can be described as a multi-objective partial covering problem. The problem is multi-objective because it has to deal with two conflicting objectives as shown in chapter 4. Furthermore, the problem is not a set covering problem but a partial covering problem because it does not cover all demand but only the demand within the decision space of the objectives.

The facility location problem for charging stations can be characterised as static and deterministic because both electric vehicles and charging stations are static elements in the model. The charging stations are static because when simulations are run the charging station have a fixed location just as in the real-world. The electric vehicles in the model are also static; the distribution of electric vehicles in the model is further explained in paragraph 5.3. The location problem is deterministic because the model will always produce the same output given the same starting values and initial state, which is further explained in paragraph 6.1.

5.2.3 Solving the facility location problem for the model

For solving the location allocation problem, a heuristic method will be used. Heuristic methods have been proposed to solve standard location allocation problems, as exact solutions are often not computable given the size of the problem or the form of the objective function in an application (Arentze, 2010). A heuristic method will not provide the ultimate solution through exhaustive research but it will provide a satisfactory solution through rational shortcuts.

After simulations are run several criteria will be used to identify solutions for the location allocation problem. These solutions are not ultimate solutions but near optimal solutions. Besides these criteria it is also important to visually monitor the spatial distribution of charging stations. The used criteria are explained in paragraph 8.3

5.3 Environment for the model

In this paragraph the environment and the study area for the location allocation model will be described. Since the electric vehicles form an important part of the environment, a forecast for the number of electric vehicles for the study area will be made. Then the distribution of these electric vehicles over the study area will be determined.

5.3.1 Case study - Municipality of Eindhoven

The case study for using the location allocation model is the municipality of Eindhoven. In this report the area of the municipality of Eindhoven will determine the environment for the model.

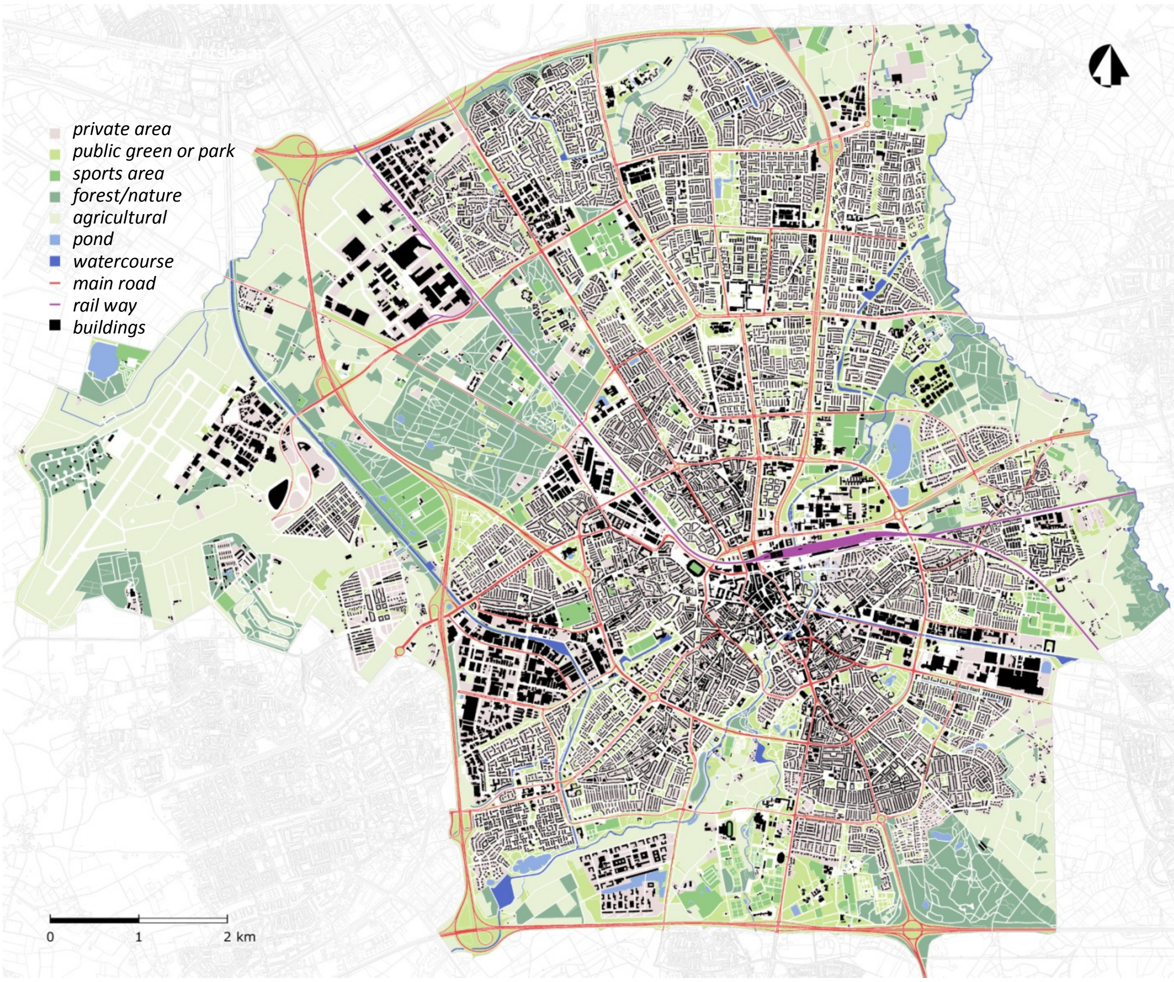

Figure 7 Map of the municipality of Eindhoven

In terms of population Eindhoven is the fifth biggest city of The Netherlands but with a population of 218.433 inhabitants (GBA, 2013) Eindhoven is a relatively small city. The municipality of Eindhoven is located in the south of The Netherlands and it has a total are of 88,87 km^2 including water. A map of the municipality of Eindhoven is shown in figure 7.

Eindhoven has the ambition to be an energy neutral municipality by the year 2045 (Municipality of Eindhoven, 2013). For being energy neutral the use of energy must be balanced; the total demand for energy must be minimised and the required energy has to be renewable energy. Energy efficiency through consumer behaviour and new technologies will greatly influence energy savings and it will reduce energy consumption. The most important renewable energy sources for Eindhoven are solar energy, geothermal energy and converging biomass into energy. Although Eindhoven is not dealing with air quality problems as Amsterdam and Rotterdam do, it is still an important objective for the municipality of Eindhoven to increase the air quality for health reasons. Achieving sustainability is not only beneficial for the environment and the health of people, it also provides economic opportunities. Local governments, businesses and research institutes have to cooperate to achieve these ambitions.

Sustainable mobility and therefore electric mobility is a crucial part of the municipality's objectives. Especially when renewable energy is used to generate electricity, electric vehicles contribute significantly to lower emissions, less noise and efficient energy usage within the municipality of Eindhoven.

5.3.2 Forecast of electric vehicles in Eindhoven

In order to determine the environment for the model a forecast of electric vehicles in Eindhoven has to be made. To determine the amount of electric vehicles in Eindhoven the objective of 200.000 electric vehicles in 2020 as mentioned in paragraph 2.3 is used. For this research it is assumed that the share of electric vehicles in Eindhoven is in proportion with the Eindhoven/The Netherlands conventional car ratio. Over the last years car ownership has been growing gradually in The Netherlands with an annual growth between 1 and 2%. It is expected that this growth will continue over the next years (Ministry of Infrastructure and Environment, 2012). Table 6 shows a 1,58% average growth of car ownership over the past years. Extrapolating this growth results in 8.835.273 cars in 2020. The municipality of Eindhoven shows a comparable trend in car ownership growth. The average annual growth of car owner ship in Eindhoven is 1,6% as shown in table 6. Through extrapolation it is assumed that there will be 108.766 cars in Eindhoven in 2020.

Year	Cars in The Netherlands	Growth (%)
2006	7.092.293	
2007	7.230.178	1,94%
2008	7.391.903	2,24%
2009	7.542.331	2,04%
2010	7.622.353	1,06%
2011	7.735.547	1,49%
2012	7.858.712	1,59%
2013	7.915.613	0,72%
2020	8.835.273	
	Average annual growth	1,58%

Year	Cars in Eindhoven	Growth (%)
2006	88.560	
2007	89.743	1,34%
2008	91.701	2,18%
2009	91.998	0,32%
2010	92.917	1,00%
2011	94.225	1,41%
2012	97.358	3,33%
2020	110.502	
	Average annual growth	1,60%

Table 6 Forecast of cars in The Netherlands and Eindhoven (CBS, 2013)

According to these trends the municipality of Eindhoven represents 1,2% of all cars in The Netherlands. Applying this proportion means that out of the 200.000 electric vehicles approximately 2.400 of them will be in Eindhoven in 2020. As mentioned in paragraph 2.2.1, this research only considers full electric vehicles and plug-in hybrid vehicles. Approximately 20% of all electric vehicles are not regular full electric vehicles or plug-in hybrid electric vehicles but (heavy) company cars, trucks, busses, motorcycles or quadricycles (AgentschapNL, 2013). According to these numbers it is assumed that for the municipality of Eindhoven the total amount of full electric vehicles and plug-in hybrid electric vehicles will be approximately 2.000 in the year 2020.

5.3.3 Distribution of electric vehicles

There are several ways to distribute 2.000 electric vehicle over the municipality of Eindhoven. First of all it must be mentioned that for a realistic distribution of the vehicles will be distributed over the neighbourhoods of Eindhoven. The municipality of Eindhoven is divided into 7 districts and 116 neighbourhoods and since the level of neighbourhoods provides the most detailed demographic information, this division will be used for the distribution of electric vehicles over Eindhoven. Secondly it is important to realise that the electric vehicles can be distributed according to the functions within the neighbourhoods. A distribution can be solely based on where owners of electric vehicles live, work or visit. For this research a combination of three functions will be used to distribute the cars over Eindhoven. These three functions are: living, working and visiting. Visiting mainly aims at shopping activities but it might also be for visiting public services, recreational areas, friend and family or other facilities. This paragraph will describe the distributions per function and the next paragraph explains how these function are combined.

To determine a distribution solely for the function living a rather straightforward approach is used. The information about car ownership per neighbourhood provided by the CBS (Statistics Netherlands), is based on the license plate registration by the RDW (Department of Road Transport) the majority of the license plates are linked with the owners' data such as residential addresses. This means that car ownership directly represents vehicles for the function living. Currently, every neighbourhood represents a different amount of cars and therefore a different density of cars. For every neighbourhood the number of cars in 2020 is based on data from CBS and calculated through extrapolation, which is shown in appendix E. Then, the 2.000 electric vehicles are divided among all the neighbourhoods according to the proportion of cars for each neighbourhood compared to the total amount of cars in 2020. If a neighbourhood for example represent 50% of all the cars in Eindhoven in 2020 than it will also represent 50% of all electric vehicles in 2020. The calculations are shown in appendix E. The table clearly indicates substantial differences between neighbourhoods.

To determine a distribution solely based on the function working, different data from CBS is used. The distribution is based on the amount of workplaces per neighbourhood. Thereafter, the same approach is used as for the function living; the amount of workplaces is extrapolated to 2020 according to the average growth per neighbourhood over the last years. Then again, the 2.000 electric vehicles are divided among all neighbourhoods according to the proportion of workplaces for each neighbourhood compared to the total workplaces in 2020. The distribution for the function working is shown in appendix F.

Lastly, a distribution based on visiting is determined. From CBS the data about floor area for retail is used. This data does not represent all destinations for visiting purposes but since other data is not available at neighbourhood level this data is considered as most representative. The distribution is based on the square metres of floor area for retail per neighbourhood. This time a slightly different approach is used; the square metres of floor area is not extrapolated to 2020 because the total amount of floor area has been almost similar over the last couple of years. Therefore, it is assumed that this will also be the case for the next years (Municipality of Eindhoven, 2013). Again, the 2.000 electric vehicles are divided among all neighbourhoods according to the floor area for sales for each neighbourhood compared to the total floor area. The distribution for the function visiting is shown in appendix G.

The three previously described distributions do not present a final distribution for the electric vehicles in 2020. All functions will have to be integrated to create one final distribution. However, there is a problem when it comes to integration all three functions; all distributions assume that the electric vehicles are static at all times which is obviously not the case. The next paragraph will explain how to deal with this problem.

5.3.4 Electric vehicle usage during a day

The number of electric vehicles per neighbourhood, regardless for which function, will change over time simply because vehicles are used for transportation which involves movement which cannot be ignored. To determine the movement of cars in and between neighbourhoods, everyday life and locations of people during the day have to be examined. The daily patterns determine where electric vehicle drivers - and so electric vehicles - are located and when. For the distribution of electric vehicles a distinction is made between the following locations: at home, at work and at facilities. Besides these location it is possible that electric vehicle users are travelling, meaning that the vehicle is no longer static and so it cannot be recharged. The percentage of electric vehicles travelling at a certain point of time during the day is subtracted from the total amount of 2.000 electric vehicles. As a result the model will only consider electric vehicles which are static and rechargeable.

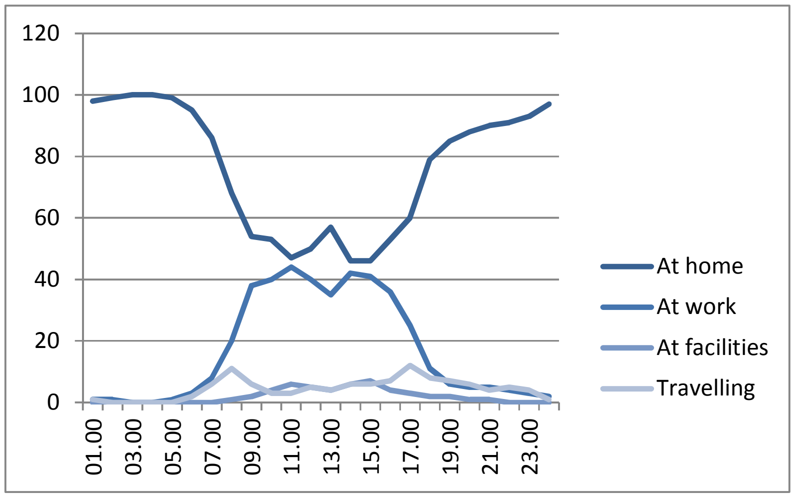

Figure 8 Locations of people during a day (SCP, 2011)

The Netherlands Institute for Social Research (SCP) has studied the general patterns and activities of people in The Netherlands during a day. The activities of interest for this research are the ones where people are either at home, at work, at shops and other facilities or when people are travelling. Appendix H shows several graphs which provide information about where people are over the course of a day. Since The Netherlands Institute for Social Research does not provide specific information about being at home it is assumed that when people are not at work, at facilities or travelling they are at home. In figure 8 and table 7 this information is combined and for every hour of the day the percentage of people at a specific location is indicated. The total number of electric vehicles differs per hour of the day, because the travelling electric vehicles are left out. Travelling vehicles are left out because they are unable to recharge and so the model will not consider them for the location allocation of charging stations.

Location	At home	*At work*	*At facilities*	*Travelling*	Total (%)	Total EV's
Time						
01.00	98	1	0	1	100	1980
02.00	99	1	0	0	100	2000
03.00	100	0	0	0	100	2000
04.00	100	0	0	0	100	2000
05.00	99	1	0	0	100	2000
06.00	95	3	0	2	100	1960
07.00	86	8	0	6	100	1880
08.00	68	20	1	11	100	1780
09.00	54	38	2	6	100	1880
10.00	53	40	4	3	100	1940
11.00	47	44	6	3	100	1940
12.00	50	40	5	5	100	1900
13.00	57	35	4	4	100	1920
14.00	46	42	6	6	100	1880
15.00	46	41	7	6	100	1880
16.00	53	36	4	7	100	1860
17.00	60	25	3	12	100	1760
18.00	79	11	2	8	100	1840
19.00	85	6	2	7	100	1860
20.00	88	5	1	6	100	1880
21.00	90	5	1	4	100	1920
22.00	91	4	0	5	100	1900
23.00	93	3	0	4	100	1920
24.00	97	2	0	1	100	1980

Table 7 Location in percentages per hour of the day (SCP, 2011)

5.3.5 Integrated distributions of electric vehicles

Now that the distributions for the functions living, working and visiting plus the locations of electric vehicles during the day are known the data can be integrated. For every neighbourhood the amount of electric vehicles for every hour of the day can now be calculated as indicated in the following example. Table 7 indicates that at 10.00 AM of all electric vehicles 53% is at home, 40% is at work, 4% is at facilities and another 3% is travelling meaning that in total there are 1.940 static or parked electric vehicles. For a specific neighbourhood during that hour of the day the total number of electric vehicles will be comprised of 53% of that neighbourhood's proportion for *living* plus 40% of that neighbourhood's proportion for *working* and 4% of that neighbourhood's proportion of *visiting.* In other words, instead of only considering *one* function for a 100%, all functions are now considered according to the percentages for each specific hour of the day. This way the movement of electric vehicles is represented by using intervals. In a way every distribution per hour of the day represents a snapshot of where electric vehicles are. The distributions for every hour of the day are shown in appendix I.

To illustrate the movement of electric vehicles, snapshots are created for every hour of the day representing a distribution of electric vehicles for each specific moment.

5.3.6 Final distribution

A final distribution is needed because in the real world charging stations are static and the model needs one distribution to determine the locations of charging stations with. The locations of charging stations need to meet the demand for charging during the whole day. As appendix I demonstrates, some neighbourhoods show high fluctuations on the number of electric vehicles during a day. Periods with high numbers of electric vehicles compared to others cannot be ignored and they need to be integrated in a final distribution. Especially neighbourhoods which are primarily working or shopping areas such as Binnenstad, Fellenoord, High Tech Campus and Flight Forum, indicate high fluctuations between the amount of electric vehicles during business hours and other hours of the day. These peaks cannot be ignored because they represent an essential part of the total demand for charging stations. To integrate these peaks two questions have to be answered: Which neighbourhoods show fluctuations of electric vehicles during the day and when are these fluctuations substantial? And secondly, which part of the day shows fluctuation?

To answer the second question, graphs are created for every neighbourhood over the course of a day. These graphs are shown in appendix J and they reveal that in almost all cases there is a difference between the amount of electric vehicles in a neighbourhood between 8 am and 8 pm. For some neighbourhoods the amount of electric vehicles increases during this period and for others it decreases. Generally, the two periods represent day-time and night-time. Although periods have been identified, the question whether a fluctuation between the two periods is substantial still remains. To determine if a fluctuation is substantial the averages of both periods are calculated and compared. If the ratio between these averages is higher than 1,5 the fluctuation is considered to be substantial.

To calculate a final distribution, for all neighbourhoods presenting a substantial higher or lower amount of electric vehicles between the two periods are selected. From this selection the average number of electric vehicle during day-time or night-time is used. In other words, for all neighbourhoods that show a substantially higher or lower number of electric vehicles over a period of time, the averages of this period is used for a final distribution. For all the other neighbourhoods which show no substantial difference the average of electric vehicles over all 24 hours is used for a final distribution.

The table in appendix K shows the final distribution of electric vehicles over all neighbourhoods within the municipality of Eindhoven. This distribution is not the ultimate distribution but it represents the average electric vehicles per neighbourhoods including peak and off-peak hours. It is a snapshot which represents the assumed locations of all electric vehicles considering all hours of the day, all three functions and the locations of drivers. Appendix K also indicates that the total number of electric vehicles is 2.107 instead of 2.000. This increase of electric vehicles seems odd since the forecast for electric vehicles in 2020 assumes 2.000 vehicles. The increase of electric vehicles can be explained because the final distribution takes into account that electric vehicles might have to recharge at different places during a day. So, an electric vehicle can be represented at more than one location during a day. The distribution of vehicles for the model does not partially represent electric vehicles, so a slight increase of vehicles to represent them during a whole day is inevitable.

The final distribution of electric vehicles combines all snapshots into one representative distribution.

5.4 GIS

As mentioned in chapter 1.3, this research combines GIS and agent-based to construct the location allocation model for public charging stations. Geographic information systems are used to gather, analyse, modify, manage and present all types of spatial information. GIS is an operational and supporting information system where data can be related to a specific location or area. Combining data with geographic information such as maps, results in numerous forms of output. With GIS many products can be created such as maps, charts, tables and graphs. GIS is commonly used in planning, analysis of traffic, transport, environment, safety, earth sciences and many more applications.

There are various software programs available for using GIS. For this research the open source software Quantum GIS is used. Quantum GIS is a user friendly geographic information system which supports numerous vector, raster and database formats (QuantumGIS, 2013).

Now that a final distribution of electric vehicles is created this data can be used to generate maps. In QuantumGIS the data is first linked to a map of Eindhoven with all the neighbourhoods. This map is based on a Amersfoort RD New projection. A characteristics of these projections is the use of a Cartesian coordinate system which is a orthogonal system. Next the data is used to create random points within every neighbourhood. Maps are created with random distributions of all 2.107 electric vehicles. It must be noted that the points are electric vehicles represented at the locations where people live, work or visit. For the model it is assumed that electric vehicles are located wherever their drivers are. In reality the location of a parked vehicle and the location of the driver is not the same. Furthermore, the points are randomly distributed per neighbourhood so they do not represent a completely accurate or optimal location of electric vehicles. In chapter 8.1 the use of multiple random distributions will be explained more detailed.

The created maps are exported as shape files so they can be used in Netlogo. The software program Netlogo is described in more detail in the next paragraph.

5.5 Programming the model

In this paragraph the software program used for creating the model and the specific agents in the model are described. The structure of the program will be explained followed by a more detailed description of the agents and their features.

5.5.1 Netlogo

In order to create the location allocation model which combines agent-based modelling and GIS the program Netlogo is used. There are several reasons why Netlogo has been chosen for creating the model. First of all, Netlogo is a programmable modelling environment for simulating natural and social phenomena. As a free and open source system Netlogo is a relatively simple system but well suited for modelling complex systems. Although a relatively simple system Netlogo can serve as a powerful tool for researchers in many fields (Wilensky, 1999). Netlogo is designed primarily for agent-based models of mobile individuals with local interactions in a grid space. Finally, Netlogo is highly recommended, even for prototyping complex models (Railsback, 2006).

Netlogo uses four kinds of agents: turtles, patches, links and the observer. Turtles are the agents that move around in the environment. The environment of the model consist of a grid of patches. Each patch has coordinates and is a part of the environment of which turtles can move. A patch's coordinates are always integers but a turtle's coordinates can have decimal meaning that a turtle can be located at any location within a patch. Links do not have coordinates but they are visual lines connecting two or more turtles. If one of the connected turtles dies then so does the link. The observer gives instructions to all other agents and it can make new turtles. Commands and reporters tell agents what to do which results in some effect. When commands and reporters are not built in primitives but defined by the creator they are called procedures. Agent variables are places to store values in an agent. Agent variables can be global variables, turtle variables, patch variables or link variables. Netlogo uses built in variables such as colours or coordinates but also variables defined by the creator (Wilensky, 1999).

5.5.2 Turtles

The model uses two kinds of turtles; electric vehicles and charging stations called chargers. In Netlogo these types of turtles are called breeds. Every breed has its own behaviour, constraints and requirements which influences the environment.

The random points created with GIS represent electric vehicles. In Netlogo they are transformed into a breed of turtles called evs. The electric vehicles have coordinates in the Netlogo environment and they remain static. Although they do not move around in the environment they do influence it because they own the variable serviced. An electric vehicle can be either serviced or not meaning that it is covered by a charging station or not. The electric vehicles also have a colour in the model; green points are serviced vehicles and red points are vehicles which are not serviced. The status of an electric vehicle will then influence the behaviour of charging stations moving around in the environment.

The charging stations, which are called chargers in the model, also represent a breed of turtles and thus own different variables than electric vehicles. Initially there are no charging stations in the environment but according to the behaviour of the stations they will arise when they identify a location which answers to the objectives. In the model a charging station then "sprouts". The charging stations own many variables which are all described in part 2 of this report. In the model these variables are represented as sliders in the interface so the decision space of the stations can be adjusted which changes the behaviour of the stations. The charging stations are influenced by the electric vehicles because it will count the number of electric vehicles within its catchment area which are not serviced.

5.5.3 Patches

The environment of the model is represented by a grid of cells called patches. As mentioned in paragraph 5.3.1, the total area of the municipality of Eindhoven is 88,87 km^2 or 8.887 ha. The environment used by Netlogo is rectangular and does not use the exact borders of the municipality. This means that the length and width of the rectangular environment is determined by maximum length and width of the municipality. The RDnew map in GIS shows that the maximum horizontal distance is 13.207 metres and that the maximum vertical distance of the municipality is 10.700 metres. As a result the total environment of the model has a surface of 141,31 km^2. For the model to be detailed enough it is desired that the size of one patch is at most 50 by 50 metres representing 2500 m^2 which is a quarter of a hectare. Considering the maximum radius of a charging station the size of the patches is set at 40 by

40 metres. As a result the total rectangular environment is comprised of 268 by 330 patches, which is in total 88.440 patches. Of all these patches approximately 55.544 patches will cover the area of the municipality.

5.6 Conclusion

In this chapter the approaches and conditions for creating the location allocation model have been clarified. This chapter answers to the sub question: Which approaches can be used to create a location allocation model and how can they be combined?

Agent-based modelling and GIS are combined to enable the creation of the location allocation model. Agent-based modelling is a simulation technique for modelling complex systems. Within agent-based modelling systems are modelled as a set of entities called agents. The agents are self-contained, autonomous entities which interact with each other and their environment. For creating the model the program Netlogo is used. Netlogo is a programmable modelling environment for simulating natural and social phenomena and it is designed primarily for agent-based models of mobile individuals with local interactions in a grid space.

A geographic information systems (GIS) is an operational and supporting information system where data can be related to a specific location or area. GIS is used to gather, analyse, modify, manage and present all types of spatial information. Combining data with geographic information such as maps, results in numerous forms of output. With GIS many products can be created such as maps, charts, tables and graphs.

To determine the environment for the location allocation model a distribution of electric vehicles is created. First the movement of electric vehicles over the course of a day is illustrated by creating snapshots of distributions for every hours of the day. For every neighbourhood the functions living, working and visiting are combined with the locations of electric vehicles over the course of a day. As a result every neighbourhood has a different distribution of electric vehicles for every hour of the day. Finally this data is used to create one final distributions which combines all snapshots into one representative distribution for the whole municipality.

With GIS the final distribution is used to created maps which in turn are loaded into Netlogo and forms the environment of the model. In a nutshell this is how the used approaches are combined.

Chapter 6 Design of the model

In the previous two chapters the objectives, variables and conditions for the model have been described. Most of the formulas and settings explained in the previous chapters will be represented here as well. In this chapter the design of the model is described in more detail. The programming codes of which the location allocation model is built will be explained step by step. Furthermore, the procedure determining the behaviour of the turtles will be explained. The model and the design of the model can be regarded as the junction of this research where all input, variables, assumptions and conditions are combined into one model.

6.1 Setting up the model

The model has two buttons to run a simulation; the setup button and the go button as shown in figure 12. When the setup button is used the model responds by (re)setting the model to the initial state. The setup button also clears all previous settings and simulations. When the initial state is set, simulations can be run. In this paragraph the procedures of the setup button will be described in detail.

Code

```
to setup
  clear-all
  random-seed 1

  set eindhoven-dataset gis:load-dataset "Eindhoven_totaal.shp"
  set evs-dataset gis:load-dataset "FinalFinal1.shp"

  gis:set-transformation gis:envelope-of eindhoven-dataset
       (list min-pxcor max-pxcor min-pycor max-pycor)
  gis:set-transformation gis:envelope-of evs-dataset
       (list min-pxcor max-pxcor min-pycor max-pycor)

  gis:set-world-envelope
       (gis:envelope-union-of (gis:envelope-of eindhoven-dataset)
                              (gis:envelope-of evs-dataset))

  gis:set-drawing-color white
  gis:fill eindhoven-dataset 1

  foreach gis:feature-list-of evs-dataset [
    let location gis:location-of (first (first (gis:vertex-lists-of ?)))
    create-evs 1 [
      set shape "circle"
      set serviced? "false"
      set color red
      set size 1
      set xcor item 0 location
      set ycor item 1 location
      ]]
  reset-ticks
end
```

The *clear-all* procedure resets the world to an initial and empty state. Basically, it starts with a clean sheet where all the patches turn black and all turtles will disappear. The procedure *random-seed 1* allows that simulations can be reproduced with the exactly same outcomes. As a result the model will be deterministic which is important for scientific modelling. With a random-seed the simulation remains random but it uses the same sequence of random numbers from then on. This way the same results will be generated, which is called a deterministic process. To generate different outcomes a different random-seed will have to be used. The random number generator used by Netlogo is known as the Mersenne Twister (Wilensky, 1999).

The codes *set eindhoven-dataset* and *set evs-dataset* are used to load the GIS shape files into Netlogo. The *Eindhoven-dataset* is a map of Eindhoven with all neighbourhoods and the *evs-dataset* is the distribution of electric vehicles. The *set-transformation* code defines a mapping between the RD new coordinates from GIS and the Netlogo coordinates. For both datasets *set-transformation* considers the minimal and maximal coordinates on the x-axis and the y-axis and it reports an envelope (bounding rectangle) for each dataset. The code *envelope-union-of* unifies the two envelopes into one *world-envelope*.

Although the distribution of electric vehicles is loaded into Netlogo by using the *evs-dataset*, they are not turtles yet. The last part of the setup ensures that the features represented in the *evs-dataset,* which are the electric vehicles, are converted into turtles. The electric vehicles are initially all set as red dots and they are not yet covered or serviced by a charging station so *serviced?* is set *false.*

After pressing the setup button the initial state of the model is set. The environment with a map of the municipality of Eindhoven and a distribution of electric vehicles as turtles, is now visible. An example is given in figure 9.

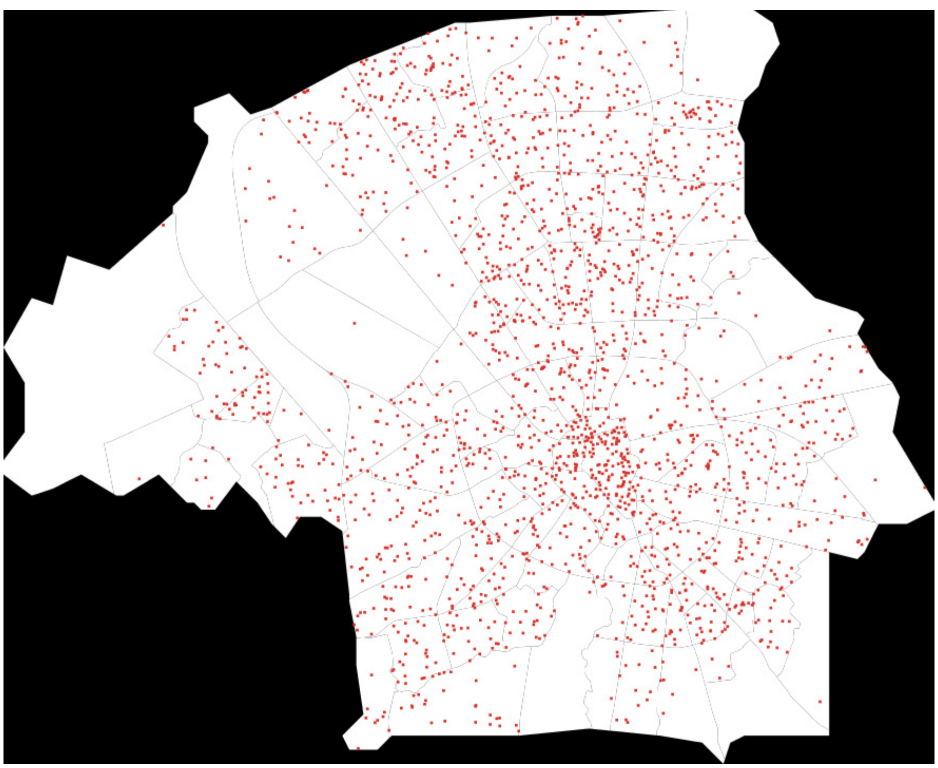

Figure 9 Map with distribution of electric vehicles

6.2 Calculating scores

Depending on its location and direct surroundings, a charging station obtains a certain score. The score of a charging station will eventually determine if a location is suitable or not. In this paragraph the calculations for the score of a charging station will be explained. The calculations correspond directly to the calculations in chapter 4. The difference is that in the procedure no abbreviations are used to make the variables in the interface more understandable.

Code

```
to-report calculate-score-radius4
  let score1
    (1 - ((count evs with [serviced? = "false"] in-radius 4 * distance-travelled
     per- ev * energy-consumption-per-ev) /
     (outlets-per-station * power-per-point * actual-charging-time)))

  ifelse (score1 >= 0)
         [ set score1 1 ] [ set score1 0 ]

  let score2
    ((count evs with [serviced? = "false"] in-radius 4 * distance-travelled-per-ev*
     energy-consumption-per-ev) /
     (power-per-point * outlets-per-station) /
      24)

  ifelse (score2 >=
    ((initial-capital-investment * ((1 + annual-rate-of-return) ^ depreciation-
     period)) * (((1 + interest-rate-loan) ^ depreciation-period) * interest-rate-
     loan) /
     (((1 + interest-rate-loan) ^ depreciation-period) - 1)) /
     (((energy-selling-price - energy-purchase-price) * outlets-per-station *
     power-
     per-point * 365) - (annual-operating-costs + annual-maintenance-costs +
     annual-
     network-costs)) /
     24)
         [ set score2 1 ] [ set score2 0 ]

  report (score1 + score2)
end
```

The code above calculates the score of a charging station with a maximum catchment area. As mentioned in chapter 4.2.1, the maximum radius for a charging station is approximately 200 metres. With *radius4* the radius of a charging station is set at 4 patches from the centre of the patch where the station is located. This means that the radius is four times the size of a patch plus the distance from the centre to the edge of the patch. Since a patch is 40 by 40 metres, the maximum radius is set a 180 metres.

The code starts with the calculations for the first objective which is availability. The charging station counts the number of electric vehicles within the catchment area which are not services with the procedure *count evs with [serviced? = "false"] in-radius 4.* With *let score1* the constraint that demand may not exceed supply, as mentioned in paragraph 5.2, is calculated. The *ifelse* part dictates that if score1 is higher or equal to 0 the score will be set at 1 and if not then the score will be set at 0. In other words if demand does not exceed supply the score will be set at 1.

The second part of the code, starting with *let score2*, calculates the second objective which is profitability. The codes for score2 calculate the actual daily utilisation as mentioned in paragraph 4.3. For this part too, only the electric vehicles within the catchment area which are not serviced are considered. The *ifelse* part relates to the constraints for profitability and it states that the actual daily utilisation must be higher or equal than the required utilisation for profitability. Once again, if score2 is higher or equal to the required utilisation the score is set a 1 and if not then the score will be 0. The last part of the calculations, *report (score1 + score2)* adds the two scores together and then reports this number. The sum of scores will be the final output of these calculations and this output will be used to allocation locations for charging stations.

6.3 Running the model

As mentioned and shown in paragraph 6.1 the model has a setup and go button. This paragraph will explain the procedure for the go button. When the go button is pressed a simulation starts and charging stations will appear.

Code

```
to go
  ask patches [ if calculate-score-radius0 = 2 [
                 sprout-chargers 1 [
                   ask evs in-radius 4 [ set serviced? "true" set color green]
                     set shape "circle"
                     set color black
                     set size 1.5 ]]]

  ask patches [ if calculate-score-radius4 = 2 [
                 sprout-chargers 1 [
                   ask evs in-radius 4 [ set serviced? "true" set color green]
                     set shape "circle"
                     set color black
                     set size 1.5 ]]]
  tick
end
```

After the go button is pressed all patches are asked one by one to first calculate their scores within an action radius of 20 metres. If a patch scores 2, a charging station is created and all electric vehicles within a radius of 180 metres are set as serviced. When all patches are done the same process is repeated but now the scores are calculated within the maximum action radius of a charging station which is 180 metres. When all patches are done the simulation is complete and all locations are allocated. The flowchart in figure 10 illustrates the steps taken by the model to allocate locations for public charging stations.

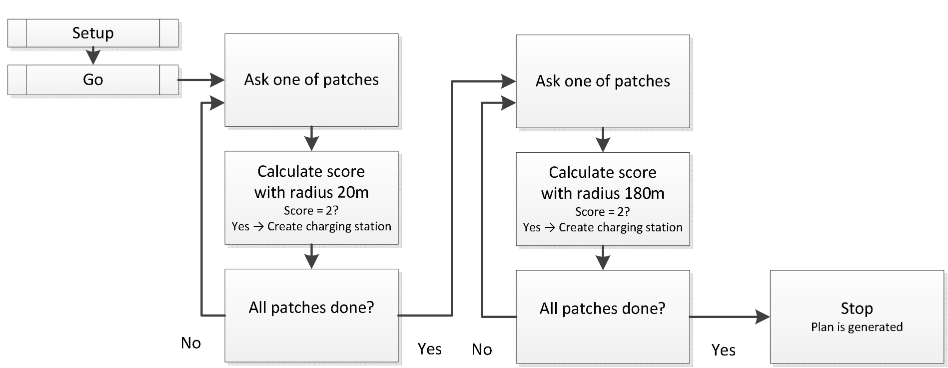

Figure 10 Flowchart Netlogo model

The *random-seed* in the setup procedure determines the sequence of patches for the calculations and therefore the simulation can be reproduced. Different radiuses are used to deal with areas with a high density of electric vehicles. When only the maximum radius is used it is possible that a location with a high density of electric vehicles is not within the decision space of the model because demand exceeds supply and therefore the location is not within the decision space. However a charging station will be desirable in this case. To solve this problem different radiuses are used in the model. The model uses a minimum and a maximum radius to allocate locations for charging stations. The minimum radius is 20 metres which is the size of a patch and the maximum radius is 180 metres which is assumed to be the maximum walking distance from station to destination. If the calculated score for a patch is 2 it means that it answers to both objectives and that a location is within the decision space of the location allocation model. If the score is 2 a charging station is created with *sprout-chargers 1*. When a location for a charging station is allocated the electric vehicles within the radius of this station will be set *serviced? "true"* because they are now covered by a charging station. For the calculations of other patches these electric vehicles will not be considered because they are already covered by a station. All vehicles which are serviced will turn from red to green. The charging stations are shown as black dots which are slightly larger than the electric vehicles. An example of a simulation is shown in figure 11.

Figure 11 Map with results after simulation

6.4 Interface

The interface is used operate the location allocation model and it shows all the buttons, sliders and monitors for running simulations. Besides these elements it also has a view which shows the map of Eindhoven and the locations of the charging stations as shown in figure 11. An overview of the interface with all buttons, monitors and sliders is shown in figure 12.

The setup and go buttons are used to run the simulations as explained in paragraphs 6.1 and 6.3. The monitors which are coloured beige, display the number of electric vehicles, charging stations and the number of electric vehicles which are covered or serviced by a station. The last monitor displays the average number of covered electric vehicles per charging station. When series of simulations have been run these monitors provide output for the analysis of the simulations.

The sliders in the interface are coloured green and they represent the variables mentioned in chapter 5. The user of the location allocation model can set the variables to the preferred or expected values. By altering the values of the variables the decision space of the model will be altered accordingly. It is obvious that number of possible combinations with all these variables is immense. The interface and the view is used for both input and output, because the sliders provide the model with input and the monitors and view provide output when simulations have been run.

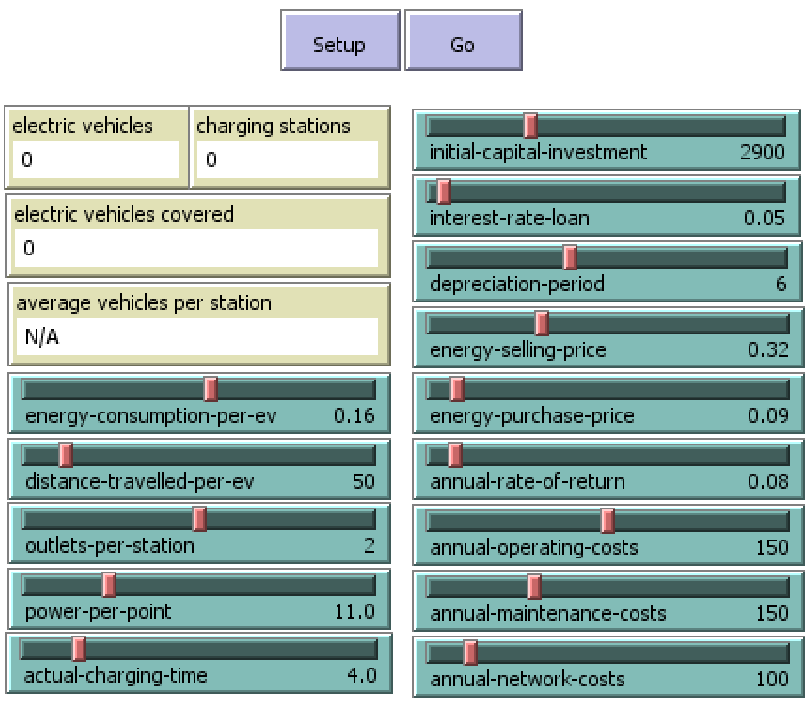

Figure 12 Interface

6.5 Conclusion

In this chapter the design of the model and all the procedures used in the model have been explained. With the setup and go button, simulations are run based on the predetermined values for the variables. When a simulation is run charging stations are allocated to locations and when a simulation is completed the monitors and the view of the map provide output.

The location allocation model can now be used to run simulations but first the values for all variables will have to be determined. The next chapter will focus on setting the values and running simulations with the location allocation model.

PART 4 SCENARIOS & SIMULATIONS

Chapter 7 Scenarios

This chapter starts with explaining the use of scenarios followed by a description of scenario analysis and the use of scenario analysis. Next, a base case scenario is developed to set the values for all variables in the location allocation model. This chapter together with the next chapter will provide an answer for the final sub question of this research: how can a case study and scenarios be used to apply a location allocation model to the real world? After chapter 8 this question will be answered.

7.1 Scenario analysis

The use of scenarios stimulates strategic thinking and helps to overcome thinking limitations by creating multiple futures (Amer, 2012). Scenarios can be described as: “a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points” (Kahn, 2000). Scenarios can also be defined as a description of a future situation and the course of events which allows one to move forward from the actual to the future situation. Scenarios do not predict the future but it explores multiple plausible future situations with the purpose of extending the sphere of thinking of the participants in the scenario development process. In other words, scenario development creates a better understanding of plausible future developments by looking at trends on a macro level such as: socio-cultural, technological, ecological, political and economic developments.

Scenario analysis is a method which maps the diversity of different scenarios. Its aim is to explore the range of possible choices, and to test how well such choices may succeed in various possible futures (Loukopoulos, 2004). Scenarios analysis can be both qualitative and quantitative although quantitative scenario analysis is more suitable for a relatively short-term. Scenario analysis plays a major role in addressing the challenges of sustainability science, especially the core question of how to scan the future in a structured and integrated manner (Swart, 2004).

7.2 Base case scenario

This scenario will present an outlook for the year 2020 which is a relatively near future scenario. A near future scenario is chosen because the electric mobility is developing quickly meaning that even in the near future there are many uncertainties and insecurities. The general assumption for this scenario is moderate growth of electric mobility in The Netherlands. As explained in chapter 3, electric mobility can generally be divided into electric vehicle developments and charging infrastructure developments.

On the electric vehicles side it is assumed that there will be approximately 2.000 electric vehicles in Eindhoven which is described in more detail in paragraph 6.4.2. The average daily distance travelled per electric vehicle is based on the average annual distance of vehicles. In 2011 the average annual distance of vehicles younger than 5 years was 18.780 km and it shows a declining trend over the past years (CBS, 2013). For this scenario the annual distance travelled per electric vehicle is assumed to be between 18.000 and 18.500 km which is an average daily distance of approximately 50 kilometres. This figure also corresponds with the average commuting distance described in paragraph 3.4.2. It is also assumed that the average electric vehicle is no longer limited to 3,7 kW charging but that the average charging capacity of electric vehicles will be 11 kW. This means that if a 11 kW charging station is used its full capacity will be used. The limitations of charging are explained in paragraph 3.4.5.

On the charging infrastructures side, it is assumed that the types and techniques used for charging stations in 2020 are comparable with the charging stations used by E-laad. This means that charging stations will have two plugs and a charging output or power of 11 kW per plug. In other words the current technology or charging stations used by E-Laad is continued and no significant improvements to the charging stations are implemented. Communications between electric vehicle drivers and charging stations have also not improved significantly meaning that the efficiency of charging stations will remain relatively low. It is assumes that electric vehicle drivers have no (financial) incentive to remove their car after it has been fully charged. As a result the assumed maximal effective charging time per day will remain low. Investment costs for public charging stations will decrease over time because it is assumed that there is a profitable business model for public charging station in 2020. The initial capital investment for a public charging station is set at € 2900,- (PRC, 2013). Since the market for public charging stations is expected to be a developing market by 2020 the annual rate of return is set at 8%. All values are shown in table 9.

Variables	Values
Average energy consumption per ev (kWh/km)	0,16
Average daily distance travelled per ev (km)	50
Number of outlets per station	2
Charging output per plug (kW)	11
Daily effective charging time per plug (hrs)	4
Initial capital investment (€)	2900
Annual interest rate for loan (%)	5
Depreciation period (yrs)	6
Energy selling price (€)	0,32
Energy purchase price (€)	0,09
Desired annual rate of return (%)	8
Annual operating costs (€)	150
Annual maintenance costs (€)	150
Annual network costs (€)	100

Table 8 Values base case scenario

7.3 Conclusion

The base case scenario created in this chapters will be used to describe a possible future for the deployment of public charging stations in the municipality of Eindhoven. By using a scenario a better understanding of plausible future outcomes will be generated. The base case scenario presents an outlook for the year 2020 and assumes moderate growth of electric mobility in The Netherlands. On the vehicle side of these developments electric vehicles will be able to recharge at 11 kW and they will consume approximately 8 kWh per day. On the infrastructure side, 11 kW charging stations are used meaning electric vehicles can fully utilize the capacity of these stations. The daily maximal effective charging time is assumed to remain low because it is expected that there is no proper communication between charging station and electric vehicle drivers. It is presumed that in 2020 public charging station will have a profitable business case and that the market for public charging stations is growing towards a mature market.

Chapter 8 Base case scenario analysis

In this chapter simulations with the model will be run to find a solution for the location problem. First multiple random distribution are created and then simulations are run with the model to produce multiple solutions to the location problem. In the third paragraph all solutions for this scenario will be analysed and finally this chapter will be concluded by presenting a couple of solutions for the problem, using different criteria. The different criteria are based on possible requirement from different users of the model. Together with the previous chapter this chapter will provide an answer to the final sub question of this research

8.1 Random distributions

Before simulations can be run, multiple random distributions for the electric vehicles have to be created first. The final distribution of electric vehicles described in paragraph 5.3.6 is used to create several random distributions of the same amount of electric vehicles. Multiple random distributions are used because in the real world too electric vehicles are parked at different locations. Furthermore, the model is not capable of producing one ultimate solution to the problem. By using multiple random distributions more situations can be simulated and analysed this way an ultimate solution will be approached more closely . Even still the presented solution will be a satisfactory solution and not an ultimate solution through exhaustive calculations. In total ten random distributions are created with GIS. For every random distribution a map is created which are loaded into Netlogo to run the simulations with.

8.2 Simulations & analysis

For every random distribution twelve simulations are run which result in a total of 120 simulations. The settings for all variables are based on the base case scenario described in the previous chapter. The results of the simulations are shown in table 10. The table represents the monitors in the model which show the number of charging stations, number of serviced electric vehicles and the average number of serviced electric vehicles per charging station. As mentioned in paragraph 5.2.3 a heuristic method will be used for solving the location problem. To analyse the data in table 10 a heuristic method is used because the model will not provide the ultimate solution but rather a satisfactory solution. For solving the location allocation problem, criteria are formulated. According to these criteria or rules the best solution within the provided set of solutions is identified. The next paragraph will explain these criteria and the result according to these criteria.

8.2.1 Maximal facilitation

The first criterion for which the data will be analysed is that the number of serviced electric vehicles must be maximised. In other words, a solution is identified as the best solution when facilitation is maximised. This criterion could be important for local governments and municipalities. The municipality of Eindhoven for example could have the ambition to facilitate as many vehicles as possible. This criterion will then be used to identify the best solution. For the users themselves this criteria is also very important because in increases the probability that they can use a charging station within the maximum walking distance form destination to their vehicle. Applying this criterion means the simulation with random distribution 5 and random seed 6 present the best solution. This solution presents 1.995

serviced electric vehicles and 724 charging stations. For this solution a map of the municipality of Eindhoven with the locations of the charging stations is shown in figure 13.

Random seed	1	2	3	4	5	6	7	8	9	10	20	30
Random distribution 1												
Charging stations	717	708	713	707	725	717	711	716	718	708	717	721
Ev's serviced	1.973	1.954	1.966	1.960	1.976	1.980	1.956	1.962	1.989	1.967	1.968	1.976
EV's/station	2,752	2,760	2,757	2,772	2,726	2,762	2,751	2,740	2,770	2,778	2,745	2,741
Random distribution 2												
Charging stations	720	710	724	718	716	707	713	704	703	718	714	709
Ev's serviced	1.952	1.953	1.953	1.945	1.948	1.942	1.963	1.950	1.962	1.959	1.958	1.951
EV's/station	2,711	2,751	2,698	2,709	2,721	2,747	2,753	2,770	2,791	2,728	2,742	2,752
Random distribution 3												
Charging stations	695	700	708	716	709	725	710	706	713	707	699	706
Ev's serviced	1.963	1.965	1.963	1.961	1.955	1.979	1.966	1.969	1.964	1.945	1.970	1.964
EV's/station	2,824	2,807	2,773	2,739	2,757	2,730	2,769	2,789	2,755	2,751	2,818	2,782
Random distribution 4												
Charging stations	708	715	720	723	733	726	720	704	734	718	711	712
Ev's serviced	1.957	1.963	1.954	1.965	1.973	1.965	1.967	1.960	1.977	1.960	1.962	1.953
EV's/station	2,764	2,745	2,714	2,718	2,692	2,707	2,732	2,784	2,693	2,730	2,759	2,743
Random distribution 5												
Charging stations	709	703	700	699	714	724	702	707	714	712	687	713
Ev's serviced	1.971	1.993	1.967	1.964	1.967	1.995	1.971	1.971	1.977	1.969	1.963	1.968
EV's/station	2,780	2,835	2,810	2,810	2,755	2,756	2,808	2,788	2,769	2,765	2,857	2,760
Random distribution 6												
Charging stations	715	709	721	709	718	713	701	707	701	703	707	710
Ev's serviced	1.960	1.968	1.960	1.962	1.962	1.953	1.967	1.958	1.943	1.958	1.963	1.954
EV's/station	2,741	2,776	2,718	2,767	2,733	2,739	2,806	2,769	2,772	2,785	2,777	2,752
Random distribution 7												
Charging stations	720	698	721	724	715	722	730	710	697	716	710	721
Ev's serviced	1.979	1.963	1.955	1.968	1.955	1.969	1.985	1.967	1.955	1.966	1.968	1.961
EV's/station	2,749	2,812	2,712	2,718	2,734	2,727	2,719	2,770	2,805	2,746	2,772	2,720
Random distribution 8												
Charging stations	729	736	719	710	726	720	725	729	731	724	719	716
Ev's serviced	1.975	1.973	1.959	1.961	1.974	1.960	1.974	1.965	1.973	1.965	1.954	1.961
EV's/station	2,709	2,681	2,725	2,762	2,719	2,722	2,723	2,695	2,699	2,714	2,718	2,739
Random distribution 9												
Charging stations	716	724	734	735	735	741	723	732	730	722	714	718
Ev's serviced	1.963	1.973	1.975	1.988	1.971	1.974	1.959	1.983	1.967	1.966	1.970	1.975
EV's/station	2,742	2,725	2,691	2,705	2,682	2,664	2,710	2,709	2,695	2,723	2,759	2,751
Random distribution 10												
Charging stations	728	703	720	709	737	713	724	713	711	711	717	710
Ev's serviced	1.982	1.951	1.984	1.976	1.993	1.975	1.980	1.973	1.966	1.974	1.976	1.964
EV's/station	2,723	2,775	2,756	2,787	2,704	2,770	2,735	2,767	2,765	2,776	2,756	2,766

Table 9 Results simulation base case scenario

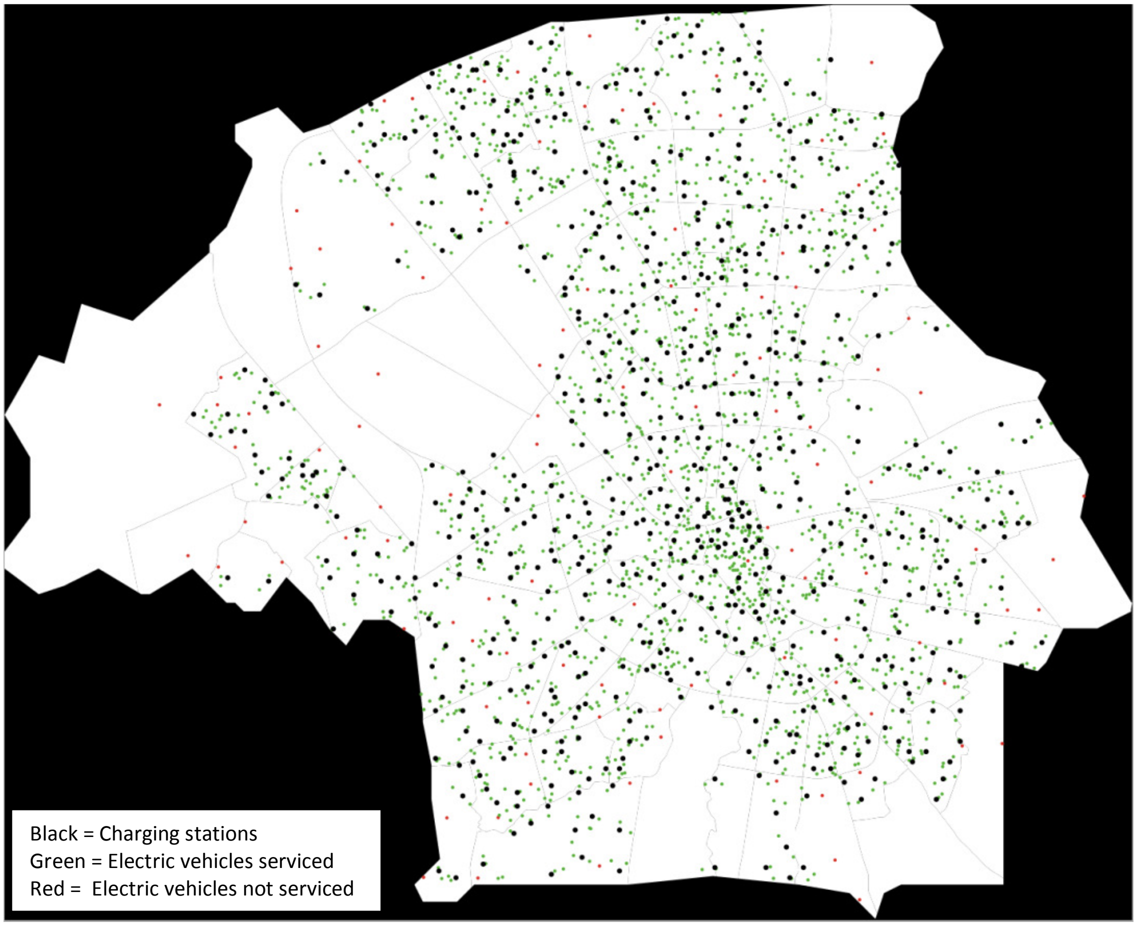

Figure 13 Map of maximal facilitation solution

8.2.2 Maximal profitability

Another goal could be to maximise the profitability of a charging station. Since the profitability is related to utilisation of a charging station the average use per charging station must be maximised. In other words the amount of serviced electric vehicles per charging station has to be maximised. This goal could be relevant to organisations which operate in a competitive market. In order to increase their return on investment the utilisation has to maximised. Operators, providers of charging services or investors are examples of businesses which aim at a maximal profitability. According to this criterion the best solution is identified as the solution with the highest average serviced electric vehicles per charging station. Applying this criterion means that the simulation with random distribution 5 and random seed 20 presents the best solution. According to this solution 1.963 electric vehicles are serviced with only 687 charging stations. For this solution a map of the municipality of Eindhoven with the locations of the charging stations is shown in figure 14.

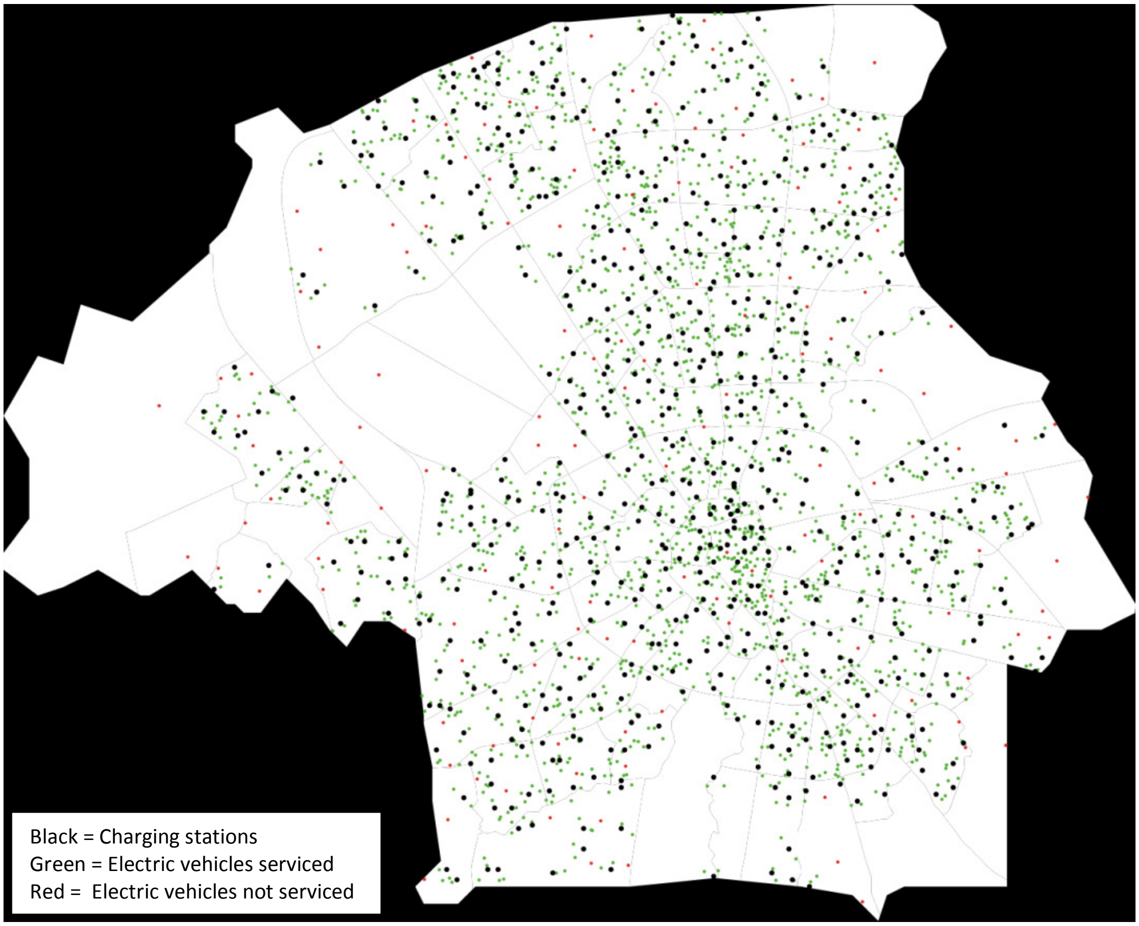

Figure 14 Map of maximal profitability solution

8.2.3 Maximal availability

A criterion can also be that the average availability of a charging station has to be maximised. In this case a solution with the lowest average serviced electric vehicles per charging station is selected. The probability that a charging station is available will increase when the average amount of electric vehicles using a station is minimised. This criterion is especially important for the users of charging stations themselves. An increased probability that a station is available increase the mental comfort of driving an electric vehicle. Applying this criterion means that the simulation with random distribution 9 and random seed 6 presents the best solution. With this solution 1.974 electric vehicles are serviced with 741 charging stations. For this solutions a map of the municipality of Eindhoven with the locations of the charging stations is shown in figure 15.

Figure 15 Map of maximal availability solution

8.2.4 Minimal charging stations

The last criterion is that the number of charging station has to be minimised. This objective could be used when organisation aims at minimising the absolute costs for realising public charging stations or that an organisation aims at minimising spatial pollution in public areas. The municipality of Eindhoven for example could aim minimising the pollution of public areas with charging stations. Obviously for municipalities this aim has to be balanced with the objective to facilitate electric vehicle drivers. The best solution for this criterion also results in the simulation with random distribution 5 and random seed 20 which map is shown in figure 14. With this solution 687 charging stations are used which is the lowest of all 120 simulations.

8.3 Conclusion

To find a solution for the location problem the model is used to analyse the base case scenario. In total ten random distributions of electric vehicles are created and for every random distribution twelve simulations are run with the model, which resulted in 120 simulations. All of these simulations present a solution to the problem but with the use of different criteria final solutions are selected. The used criteria are maximal facilitation, maximal profitability, maximal availability and minimal amount of charging stations. Maximum facilitation might be an important criterion for municipalities because their aim is to facilitate civilians. Maximum profitability could be important for investors or providers of charging services. For electric vehicle drivers themselves, maximal availability is important because it will decrease range anxiety. The last criterion which focuses on a minimal amount of charging stations could be important for municipalities to minimise spatial pollution or when the deployment of charging stations is bound to a budget.

In total three solutions can be identified because the criteria minimal amount of charging stations and maximal profitability result in the same solutions. Although the maps showing the solutions appear to be almost equal it must be realised that they represent charging stations for the complete municipality of Eindhoven. On this scale, small differences in locations of charging stations can be significant in the real world.

This chapter in combination with chapter 7 has shown that a case study and a scenario can be used to apply a location allocation model to the real world. The study area, which is the municipality of Eindhoven, provides an environment for the model. This environment in combination with several random distributions of electric vehicles is used in Netlogo to run simulations with according to the developed base case scenario. The scenario determines the values for all variables in the model and simulations provide a set of solutions to the problem. With the use of different criteria several solutions to the location problem can be identified.

PART 5 CONCLUSIONS

Chapter 9 Conclusion

In this chapter the final results and findings of this research will be presented. The conclusion will be presented as an answer to the main research question as described in paragraph 1.2.2. Thereafter, the outcomes of the model will be concluded and finally the practicality and usefulness of the model will be described.

9.1 Answering the research question

The main question for this research is: *What model can be used to allocate locations for public charging stations?*

In order to answer the main research question this paragraph is divided in two parts. The first part describes the features and characteristics of the model and the second part will describe the applicability of the model.

The model developed in this research combines agent based modelling and GIS to create an integrated model to allocate locations for public charging stations. With GIS an environment containing a distribution of electric vehicle is created. For this research the municipality of Eindhoven is used as the environment of the model. The agent based modelling approach is applied with the Netlogo program. In Netlogo a model is built which integrates GIS and agent based modelling. The codes written in Netlogo enables agents, which are among others the charging stations and electric vehicles, to interact and to decide where to create charging stations. The process of creating charging stations is deterministic because for every simulation the with the same settings the result are identical.

The model created in Netlogo is developed to solve a location problem which is a multi-objective partial covering problem. The model is dealing with a partial covering problem because it does not cover all demand but a part of it. Two conflicting objectives determine the decision space of the model and are used to allocate locations for public charging stations. If certain points of demand are outside the decision space of the model they will not be covered. The problem can be characterised as static because the electric vehicles are static elements in the environment and when a simulation is completed the charging stations are also static elements.

The model can be applied to any (urban) area as long as demographic data about the environment and usable maps of the area are at hand. In this research the municipality of Eindhoven is used as a case study for the model. Besides an environment the model also needs a scenario or any other approach to determine the values for all the variables in the model. In this research a base case scenario is constructed with an outlook for the year 2020. To analyse multiple plausible futures multiple scenarios will have to be constructed and analysed. The model can also be used to compare the spatial influences of different policies, clients or technologies on the number and locations of charging stations.

To answer the research question it can be concluded that: A spatial model combining GIS and agent based modelling can be used to allocate locations for public charging stations by solve a multi-objective partial covering problem .

9.2 Outcomes of the model

The simulations run with the model provide a set of solutions to the location problem at hand. In this research a base case scenario is used to run simulations for the municipality of Eindhoven resulting in set of solutions. It must be realised that the solutions provided by the model are not ultimate solutions to the problem. The model itself and the scenario analysis do not use exhaustive calculations to find the ultimate solution. Instead a near optimal solutions are provided by the model. To analyse the set of solutions different criteria are used. The criteria used are: maximal facilitation, maximal profitability, maximal availability and minimal amount of charging stations. According to each criteria a different solution can be selected within the total set of solutions. The maps which show the locations of charging stations for every solution are shown in paragraph 9.3. In table 11 all solutions according to the criteria are shown. The table reveals that the criteria maximal profitability and minimal charging stations result in the same solution. This is not a complete surprise because profitability is determined by high utilisation which implies a minimal amount of charging stations covering a maximal amount of electric vehicles. For this reason this solution is the same for both criteria. In terms of electric vehicles serviced, all solutions are relatively close to each other. However when considering the amount of charging stations for every solution, the differences are substantial. Especially when the number of charging stations are expressed in cost. In the base case scenario it is assumed that the initial investment costs for realising a single public charging station is € 2900,- and this is without operating costs. From this perspective the difference between maximal facilitation and maximal profitability is over € 150.000,-.

	Maximal facilitation	Maximal profitability	Maximal availability	Minimal charging stations
Charging stations	724	687	741	687
Ev's serviced	1.995	1.963	1.974	1.963
EV's/station	2,756	2,857	2,664	2,857

Table 10 Final solution according to the criteria

The outcomes of the model do not answer the main research question but it does show that the model can be applied in a real world situation and that the results are measurable and useful. Not only to determine the amount of public charging stations but equally important where to locate charging stations.

Since municipalities and local governments are in most cases the owners of the location problem described in paragraph 1.2.1, they can use this model to gather information about how many charging station are needed and where to place them. The outcomes of this model do not specify precise locations for charging stations at street level. On a micro level the exact location of public charging station still has to be determined. This also depends on the used policies by municipalities for sites of public charging stations.

Chapter 10 Discussion and recommendation

In this chapter the functioning of the model and the conceivable improvements of the model are discussed. Additionally, recommendations for further research are made about the applicability of the model.

10.1 Discussing the model

For this research an applicable location allocation model for public charging stations is created which answers to the main research question. The performance of the model and the outcomes of the model can be discussed.

First of all the location is defined as a partial covering problem but instead it could also be defined as a maximal covering problem. In case of a maximal covering problem the number of public charging stations is known upfront and the model will allocate location to achieve maximal coverage. If the model is constructed like this it is more suitable when the amount of public charging stations to be created is limited. Transforming the current model into a maximal coverage model changes of reasonable sizes.

Secondly, the current model does not use distances between electric vehicles and a station directly. The only way distances are used is by setting the maximum radius of a charging station. The distances between vehicles and station could be incorporated in the model. With the use of average distances the model would solve a median problem or a combination between a median and a covering problem.

Thirdly, the location problem is approached as a static problem. This is obviously true because both parked vehicles and charging stations are static but vehicles can also be considered as dynamic elements in a model. This will transform a static problem into a dynamic problem which has dramatic consequences for the construction of the model. Considering electric vehicles as mainly moving elements with intermediate static periods is not a part of this research but it surely is an interesting approach. This approach will include flows of electric vehicles and queuing components. Especially for fast charging stations this approach might be very interesting because in most cases they are situated along major exit roads or high ways.

10.2 Discussing the application

The scenario analysis in this research can also be executed more extensively by applying more scenarios or different forecasts of electric vehicles in 2020. The options to apply the model to different scenarios and situations is indefinite and it requires a lot of repetitions. The model can be applied to test divergent scenarios to identify the range of desired outcomes. This way strategies can be developed to steer the roll out of a charging infrastructure into a desired direction. Furthermore, for identifying the best solution for the location problem several criteria can be combined. After the simulations a multi-criteria decision analysis can be applied to select the best solution.

The model as presented in this research is an independent tool and the applicability of this model would be increased if the use of the model was linked with policies and frameworks used by municipalities. Examples of these policies are the CROW directive as mentioned in paragraph 2.4 and the charging tree as referred to in paragraph 3.1.3. For municipalities and officials, providing a framework in which the model can be used is often advised.

10.3 Recommendations

For further research it is recommended to refine the model. The discussion in paragraph 10.1 shows that there is room for improvements. Beside those improvements, the created environment in GIS can contain more details and in Netlogo candidate locations can be indicated. This way policies can be integrated in the model because in most cases policies of municipalities provide information about locations for charging stations at street level. As mentioned before the CROW directive will be a valuable addition to the application of the model if they are integrated. As a result the model will also be applicable on smaller scales.

Furthermore it is extremely important to monitor the developments of electric mobility very closely. The future of electric vehicles is unknown and even within the relatively short period of this graduation projects radical changes within the field of electric mobility have occurred. The field of electric mobility offers great challenges but also changes. It is recommended to respond to these changes adequately and effectively. For now, electric mobility is still growing and perhaps the electric vehicles in our streets will be the standard instead of the exception in 2020.

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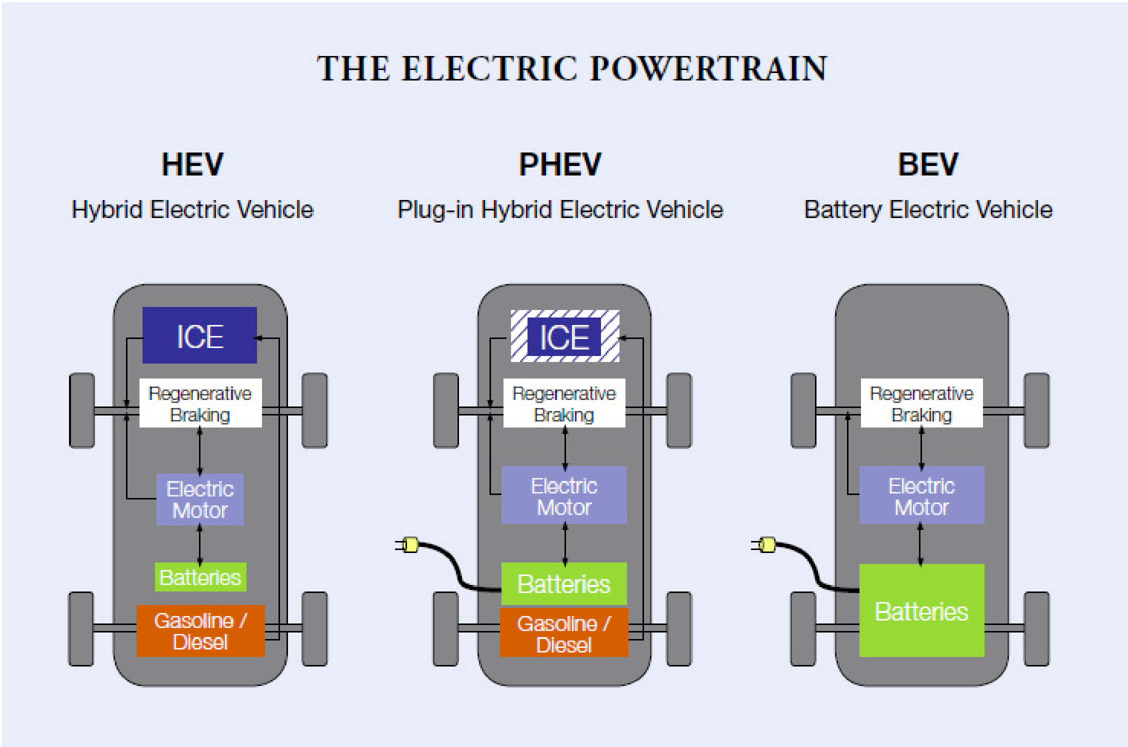
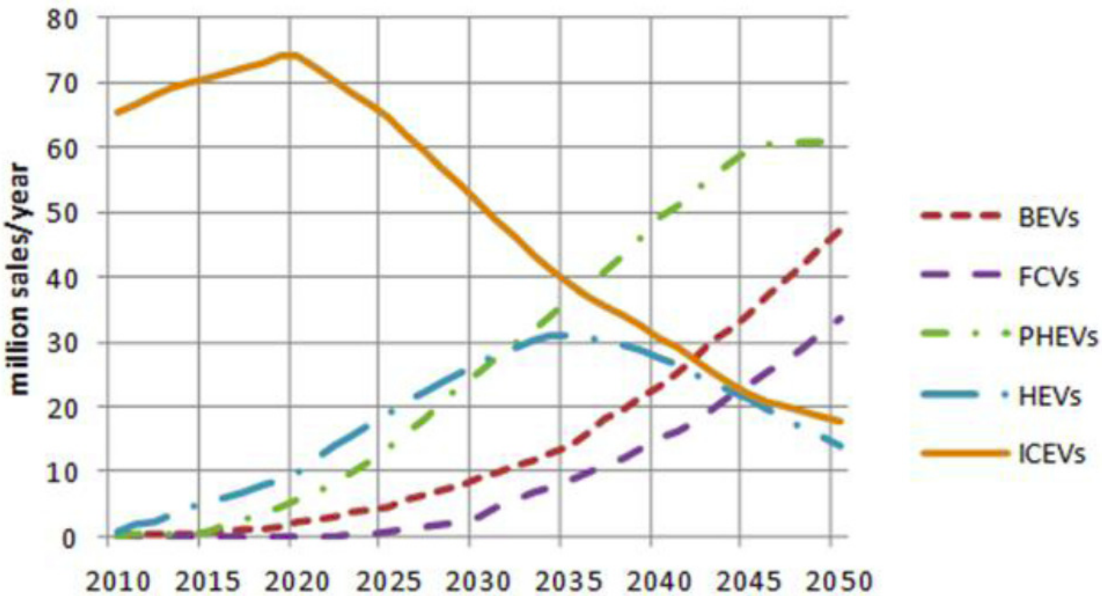
Appendices

Appendix A



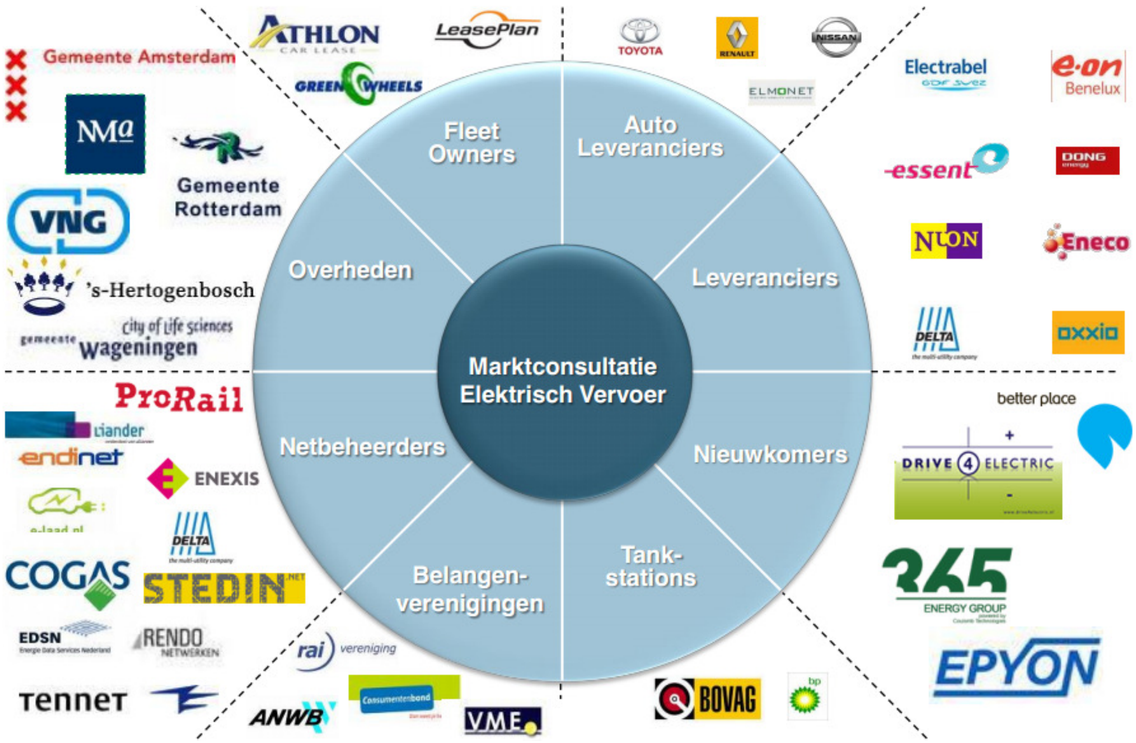
The electric powertrain (WWF, 2009)

Appendix B



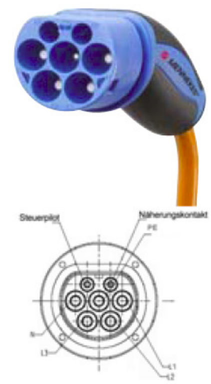
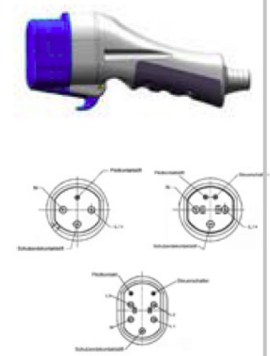
Forecast sales electric vehicles (LCA Works, 2012)

Appendix C



Stakeholder electric mobility in The Netherlands (EnergieNed, 2010)

Appendix D

Standard drafts	Draft type 1 developed in Japan	MENNEKES draft (type 2) developed in Germany	Draft type 3 developed in Italy
			
Geometry	one geometry	one geometry	three different geometries
Capacity	up to 7.4 kW up to 32A single-phase	up to 44 kW up to 63A single to three-phase	up to 22 kW up to 32A single to three-phase

Plug types (Mennekes, 2011

Appendix E Forecast electric vehicles according to car ownership

Year	2009	2010	2011	2012	2020	2020
Binnenstad	1260	1270	1270	3040	3.577	64
Bergen	865	880	850	895	1.053	19
Witte Dame	880	865	905	920	1.082	19
Fellenoord	35	25	30	25	29	1
TU-terrein	50	45	45	40	47	1
Irisbuurt	905	900	940	975	1.147	20
Rochusbuurt	480	470	505	465	547	10
Elzent-Noord	450	455	435	430	506	9
Tuindorp	950	1005	1025	1005	1.182	21
Joriskwartier	430	430	445	450	529	9
Bloemenplein	455	455	465	445	524	9
Looiakkers	190	205	205	215	253	5
Elzent-Zuid	120	110	105	115	135	2
Kerstroosplein	705	720	710	730	859	15
Gerardusplein	1110	1095	1085	1110	1.306	23
Genneperzijde	495	495	475	470	553	10
Roosten	355	355	355	365	429	8
Eikenburg	635	655	665	665	782	14
Sportpark Aalsterweg	15	15	10	15	18	0
Puttense Dreef	525	525	530	550	647	12
Poeijers	110	90	135	190	224	4
Burghplan	1120	1120	1130	1135	1.335	24
Sintenbuurt	645	655	660	715	841	15
Tivoli	540	560	555	560	659	12
Gijzenrooi	955	955	950	975	1.147	20
Nieuwe Erven	395	400	400	400	471	8
Kruidenbuurt	1015	1045	1075	1085	1.277	23
Schuttersbosch	315	310	295	285	335	6
Leenderheide	0	0	0	0	0	0
Riel	80	80	75	75	88	2
Villapark	785	835	830	840	988	18
Lakerlopen	1010	1090	1155	1160	1.365	24
Doornakkers-West	1390	1370	1385	1400	1.647	29
Doornakkers-Oost	980	980	1025	1035	1.218	22
Tongelresche Akkers	145	145	200	335	394	7
Muschberg Geestenberg	1745	1745	1790	1770	2.082	37
Urkhoven	65	65	75	80	94	2
't Hofke	1440	1440	1465	1470	1.729	31
Karpen	330	330	335	335	394	7
Koudenhoven	305	305	315	315	371	7
Limbeek-Zuid	435	435	430	435	512	9
Limbeek-Noord	765	765	775	780	918	16
Hemelrijken	1035	1045	1010	970	1.141	20
Gildebuurt	585	615	635	640	753	13
Woenselse Watermolen	485	490	500	505	594	11
Groenewoud	1310	1255	1300	1360	1.600	29
Kronehoef	1355	1400	1465	1490	1.753	31
Barrier	810	835	830	855	1.006	18
Mensfoort	1195	1190	1220	1300	1.529	27
Rapenland	1020	1010	1040	1095	1.288	23
Vredeoord	0	0	0	0	0	0
Generalenbuurt	2095	2160	2205	2285	2.688	48
Oude Toren	660	660	675	685	806	14
Hondsheuvels	60	70	75	80	94	2
Oude Gracht-West	1190	1265	1295	1290	1.518	27
Oude Gracht-Oost	705	665	690	700	824	15
Eckartdal	0	5	0	0	0	0

Driehoeksbos	560	565	555	555	653	12
Prinsejagt	1930	1935	1930	1980	2.329	41
Jagershoef	1395	1400	1415	1395	1.641	29
't Hool	815	825	835	820	965	17
Winkelcentrum	365	345	340	335	394	7
Vlokhoven	1370	1375	1395	1410	1.659	30
Kapelbeemd	185	185	180	155	182	3
Kerkdorp Acht	1955	1955	1950	1995	2.347	42
Achtse Barrier-Gunterslaer	1890	1860	1905	1940	2.282	41
Achtse Barrier-Spaaihoef	2380	2395	2420	2445	2.877	51
Achtse Barrier-Hoeven	1980	1970	1975	1980	2.329	41
Woenselse Heide	2400	2400	2315	2445	2.877	51
Tempel	2205	2245	2300	2350	2.765	49
Blixembosch-West	1025	1075	1080	1085	1.277	23
Blixembosch-Oost	3135	3115	3145	3185	3.747	67
Castilielaan	30	30	40	25	29	1
Eckart	1600	1685	1750	1765	2.077	37
Luytelaer	620	555	555	560	659	12
Vaartbroek	2325	2310	2250	2275	2.677	48
Heesterakker	1345	1355	1370	1390	1.635	29
Esp	105	95	95	85	100	2
Bokt	60	60	60	65	76	1
Eliasterrein, Vonderkwartier	1070	1160	1160	1115	1.312	23
Philipsdorp	810	825	805	780	918	16
Engelsbergen	375	335	340	405	476	8
Schouwbroek	620	620	625	635	747	13
Schoot	870	870	880	995	1.171	21
Strijp S	10	10	25	25	29	1
Hurk	510	490	470	500	588	10
Het Ven	1520	1545	1540	1560	1.835	33
Lievendaal	1105	1110	1300	1315	1.547	28
Drents Dorp	775	780	810	825	971	17
Zwaanstraat	10	30	15	10	12	0
Wielewaal	25	45	50	45	53	1
Herdgang	20	20	15	5	6	0
Mispelhoef	95	100	95	125	147	3
Beatrixkanaal-A2	20	25	25	20	24	0
Meerbos	20	35	15	15	18	0
Grasrijk	2075	2075	2105	2045	2.406	43
Bos- en Zandrijk	1330	1330	1345	1370	1.612	29
Waterrijk	250	250	350	375	441	8
Park Forum	10	10	10	15	18	0
Flight Forum	250	250	220	210	247	4
Eindhoven Airport	1	1	15	5	6	0
Bosrijk	155	155	160	185	218	4
Meerrijk	0	0	0	0	0	0
Schrijversbuurt	1245	1230	1260	1285	1.512	27
Oude Spoorbaan	695	670	675	735	865	15
Hagenkamp	420	425	425	425	500	9
Genderdal	1040	1040	1050	1070	1.259	22
Blaarthem	1065	1075	1080	985	1.159	21
Rapelenburg	245	245	265	270	318	6
Bennekel-Oost	1230	1260	1225	1205	1.418	25
Bennekel-West, Gagelbosch	1110	1120	1190	1270	1.494	27
Gennep	15	15	10	10	12	0
Beemden	10	5	5	5	6	0
Genderbeemd	1615	1665	1690	1675	1.971	35
Hanevoet	1620	1635	1670	1630	1.918	34
Ooievaarsnest	515	495	480	490	576	10

Appendix F Forecast electric vehicles according to workplaces per neighbourhood

Year	2010	2011	2012	2020	20202
Binnenstad	10.489	11.069	11.078	13.192	155
Bergen	3.275	3.282	3.170	3.775	44
Witte Dame	3.278	3.042	2.818	3.356	39
Fellenoord	7.016	7.270	6.723	8.006	94
TU-terrein	6.950	7.070	6.781	8.075	95
Irisbuurt	1.442	1.445	1.416	1.686	20
Rochusbuurt	529	494	491	585	7
Elzent-Noord	1.140	1.064	1.154	1.374	16
Tuindorp	539	511	543	647	8
Joriskwartier	222	214	250	298	3
Bloemenplein	664	641	597	711	8
Looiakkers	1.573	334	347	413	5
Elzent-Zuid	127	124	115	137	2
Kerstroosplein	475	478	297	354	4
Gerardusplein	690	735	719	856	10
Genneperzijde	888	789	807	961	11
Roosten	136	128	120	143	2
Eikenburg	438	511	512	610	7
Sportpark Aalsterweg	664	614	575	685	8
Puttense Dreef	139	144	133	158	2
Poeijers	4.202	4.409	4.800	5.716	67
Burghplan	573	570	551	656	8
Sintenbuurt	253	289	302	360	4
Tivoli	103	113	113	135	2
Gijzenrooi	232	249	226	269	3
Nieuwe Erven	311	322	343	408	5
Kruidenbuurt	281	299	288	343	4
Schuttersbosch	47	53	54	64	1
Leenderheide	0	0	0	0	0
Riel	39	41	42	50	1
Villapark	1.764	1.866	1.967	2.342	27
Lakerlopen	1.374	1.504	1.477	1.759	21
Doornakkers-West	979	1.295	1.240	1.477	17
Doornakkers-Oost	542	585	636	757	9
Tongelresche Akkers	31	45	124	148	2
Muschberg,Geestenberg	781	539	534	636	7
Urkhoven	45	50	51	61	1
't Hofke	605	669	659	785	9
Karpen	93	99	103	123	1
Koudenhoven	80	88	88	105	1
Limbeek-Zuid	358	357	384	457	5
Limbeek-Noord	418	412	425	506	6
Hemelrijken	1.888	1.866	1.925	2.292	27
Gildebuurt	852	826	792	943	11
Woenselse Watermolen	965	979	1.094	1.303	15
Woensel-West	2.168	1.957	2.204	2.625	31
Kronehoef	1.954	1.717	1.689	2.011	24
Barrier	225	249	210	250	3
Mensfort	531	564	531	632	7
Rapenland	4.770	4.871	5.304	6.316	74
Vredeoord	1.518	1.590	1.593	1.897	22
Generalenbuurt	1.400	1.426	1.192	1.419	17
Oude Toren	284	284	166	198	2
Hondsheuvels	2.071	1.779	1.810	2.155	25
Oude Gracht-West	659	680	673	801	9
Oude Gracht-Oost	956	981	977	1.163	14
Eckartdal	686	701	746	888	10

Driehoeksbos	1.126	1.262	1.261	1.502	18
Prinsejagt	400	400	483	575	7
Jagershoef	287	352	367	437	5
't Hool	113	123	123	146	2
Winkelcentrum	1.897	1.862	1.807	2.152	25
Vlokhoven	430	454	461	549	6
Kapelbeemd	4.378	4.562	5.163	6.148	72
Kerkdorp Acht	797	789	785	935	11
Achtse Barrier-Gunterslaer	3.486	3.147	3.065	3.650	43
Achtse Barrier-Spaaihoef	421	452	477	568	7
Achtse Barrier-Hoeven	459	454	454	541	6
Woenselse Heide	1.555	1.667	1.631	1.942	23
Tempel	1.624	1.712	1.696	2.020	24
Blixembosch-West	244	259	257	306	4
Blixembosch-Oost	830	853	906	1.079	13
Castiliëlaan	1.496	1.373	1.430	1.703	20
Eckart	693	680	663	789	9
Luytelaer	114	119	111	132	2
Vaartbroek	564	557	535	637	7
Heesterakker	316	300	292	348	4
Esp	1.448	1.439	1.534	1.827	21
Bokt	84	81	85	101	1
Eliasterrein, Vonderkwartier	456	479	506	603	7
Philipsdorp	1.493	1.416	1.341	1.597	19
Engelsbergen	646	616	613	730	9
Schouwbroek	416	418	349	416	5
Schoot	1.316	1.273	1.260	1.500	18
Strijp S	619	639	737	878	10
Hurk	9.758	9.861	9.795	11.664	137
Het Ven	1.768	1.707	1.658	1.974	23
Lievendaal	1.052	1.132	1.196	1.424	17
Drents Dorp	871	981	920	1.096	13
Zwaanstraat	551	553	547	651	8
Wielewaal	10	10	9	11	0
Herdgang	29	31	27	32	0
Mispelhoef	3.520	3.614	3.884	4.625	54
BeA2	57	53	32	38	0
Meerbos	87	86	88	105	1
Grasrijk	526	545	554	660	8
Zandrijk	193	203	216	257	3
Waterrijk	35	64	114	136	2
Park Forum	138	176	195	232	3
Flight Forum	7.445	7.768	7.059	8.406	99
Eindhoven Airport	218	216	206	245	3
Bosrijk	82	85	96	114	1
Meerrijk	125	134	137	163	2
Schrijversbuurt	1.079	999	1.051	1.252	15
Oude Spoorbaan	871	799	817	973	11
Hagenkamp	1.051	1.060	1.043	1.242	15
Genderdal	925	967	1.226	1.460	17
Blaarthem	497	502	870	1.036	12
Rapelenburg	218	213	182	217	3
Bennekel-Oost	467	471	503	599	7
Bennekel-West,Gagelbosch	246	257	443	528	6
Gennep	108	115	93	111	1
Beemden	5.310	6.495	5.785	6.889	81
Genderbeemd	1.454	1.455	1.372	1.634	19
Hanevoet	741	682	683	813	10
Ooievaarsnest	79	108	107	127	1

Appendix G Forecast of electric vehicles according to floor area for sales

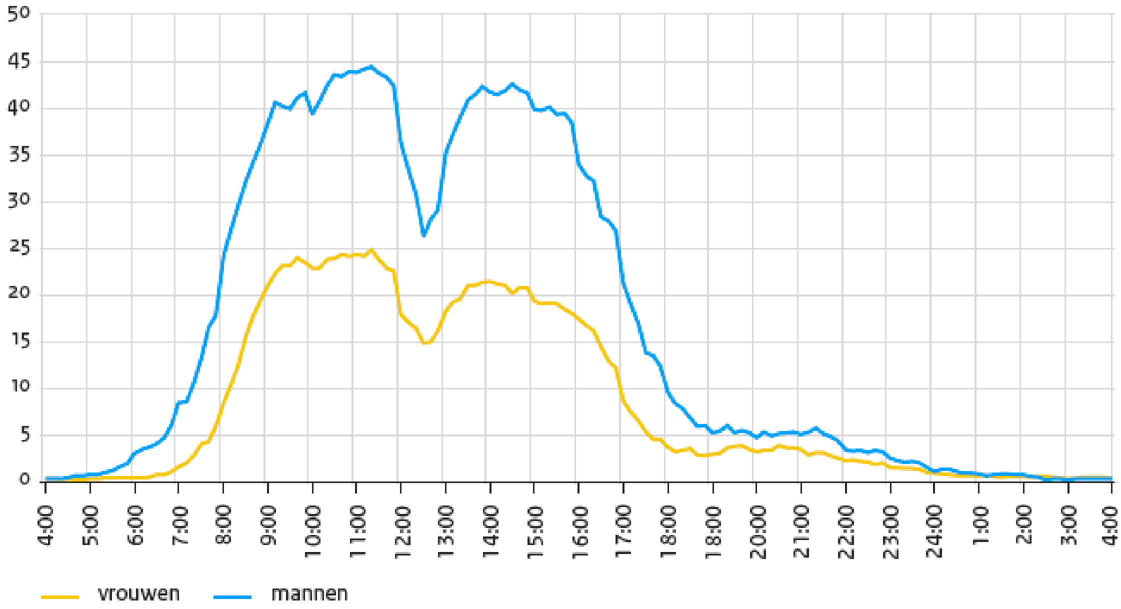
	Floor area for sales (m2)	EV's
Year	2013	2020
Binnenstad	112.687	508
Bergen	10.520	47
Witte Dame	6.795	31
Fellenoord	745	3
TU-terrein	20	0
Irisbuurt	9.500	43
Rochusbuurt	2.700	12
Elzent-Noord	1.985	9
Tuindorp	416	2
Joriskwartier	3.541	16
Bloemenplein	6.605	30
Looiakkers	3.417	15
Elzent-Zuid	0	0
Kerstroosplein	2.976	13
Gerardusplein	3.063	14
Genneperzijde	0	0
Roosten	0	0
Eikenburg	0	0
Sportpark Aalsterweg	0	0
Puttense Dreef	0	0
Poeijers	0	0
Burghplan	2.816	13
Sintenbuurt	387	2
Tivoli	295	1
Gijzenrooi	0	0
Nieuwe Erven	3.404	15
Kruidenbuurt	535	2
Schuttersbosch	0	0
Leenderheide	0	0
Riel	0	0
Villapark	2.727	12
Lakerlopen	42.251	191
Doornakkers-West	2.006	9
Doornakkers-Oost	40	0
Tongelresche Akkers	1.565	7
Muschberg,Geestenberg	1.418	6
Urkhoven	3.000	14
't Hofke	1.974	9
Karpen	0	0
Koudenhoven	120	1

Limbeek-Zuid	0	0
Limbeek-Noord	10.340	47
Hemelrijken	13.623	61
Gildebuurt	17.774	80
Woenselse Watermolen	0	0
Woensel-West	2.454	11
Kronehoef	1.014	5
Barrier	545	2
Mensfort	3.152	14
Rapenland	3.556	16
Vredeoord	0	0
Generalenbuurt	1.125	5
Oude Toren	94	0
Hondsheuvels	0	0
Oude Gracht-West	2.555	12
Oude Gracht-Oost	0	0
Eckartdal	0	0
Driehoeksbos	0	0
Prinsejagt	260	1
Jagershoef	793	4
't Hool	0	0
Winkelcentrum	32.384	146
Vlokhoven	380	2
Kapelbeemd	150	1
Kerkdorp Acht	311	1
Achtse Barrier-Gunterslaer	2.423	11
Achtse Barrier-Spaaihoef	59	0
Achtse Barrier-Hoeven	1.505	7
Woenselse Heide	3.250	15
Tempel	16.213	73
Blixembosch-West	0	0
Blixembosch-Oost	2.111	10
Castiliëlaan	0	0
Eckart	2.274	10
Luytelaer	0	0
Vaartbroek	3.958	18
Heesterakker	80	0
Esp	22	0
Bokt	45	0
Eliasterrein, Vonderkwartier	663	3
Philipsdorp	5.885	27
Engelsbergen	4.159	19
Schouwbroek	3.081	14
Schoot	4.410	20
Strijp S	746	3

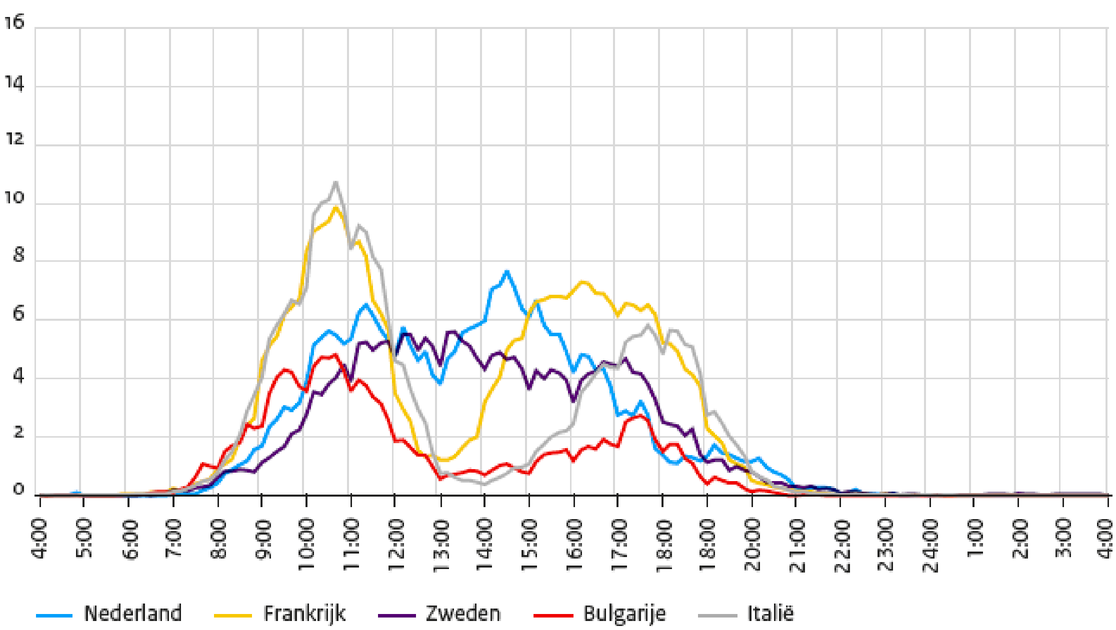
Hurk	32.581	147
Het Ven	6.898	31
Lievendaal	1.765	8
Drents Dorp	0	0
Zwaanstraat	0	0
Wielewaal	0	0
Herdgang	50	0
Mispelhoef	700	3
BeA2	0	0
Meerbos	0	0
Grasrijk	43	0
Zandrijk	0	0
Waterrijk	0	0
Park Forum	0	0
Flight Forum	0	0
Eindhoven Airport	170	1
Bosrijk	0	0
Meerrijk	6.944	31
Schrijversbuurt	4.599	21
Oude Spoorbaan	4.101	19
Hagenkamp	0	0
Genderdal	323	1
Blaarthem	2.533	11
Rapelenburg	3.668	17
Bennekel-Oost	3.356	15
Bennekel-West,Gagelbosch	634	3
Gennep	0	0
Beemden	76	0
Genderbeemd	463	2
Hanevoet	5.433	25
Ooievaarsnest	0	0
Totaal		**2.000**

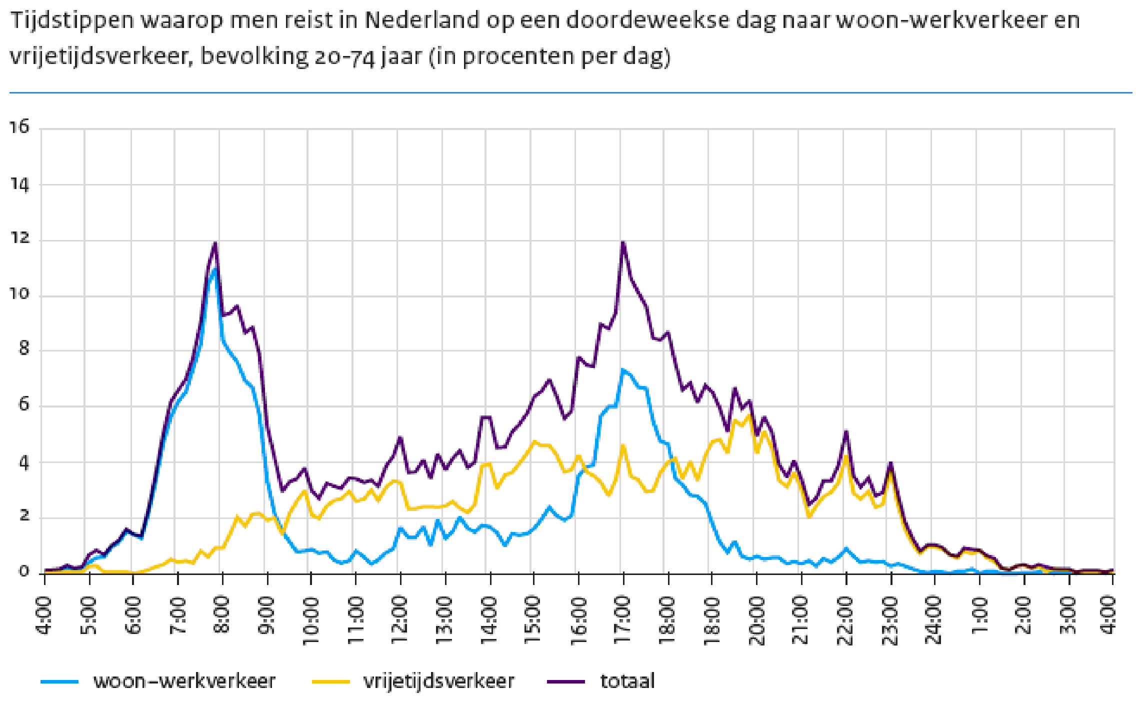
Appendix H

Tijdstippen van betaald werk in Nederland, vrouwen en mannen van 20-64 jaar (in procenten per dag)



Tijdstippen waarop men winkelt en gebruikmaakt van voorzieningen in Nederland en vier vergelijkingslanden, bevolking 20-74 jaar (in procenten per dag)





Time periods per day for working, visiting and travelling (SCP, 2011)

Appendix I

Time of the day

	AM												PM											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Binnenstad	64	65	64	64	65	65	67	79	103	116	129	119	111	125	128	110	92	78	74	69	70	64	64	65
Bergen	19	19	19	19	19	19	20	22	28	30	31	29	28	30	30	28	24	21	20	19	20	19	19	19
Witte Dame	19	19	19	19	19	19	20	21	26	27	28	27	26	27	27	26	22	20	19	19	20	19	19	19
Fellenoord	1	1	1	1	1	3	8	19	36	38	42	38	33	40	39	34	24	11	6	5	5	4	3	2
TU-terrein	2	2	1	1	2	4	8	20	36	38	42	38	34	40	39	35	24	11	6	5	5	5	4	3
Irisbuurt	20	20	20	20	20	20	19	18	19	20	21	20	20	20	21	20	18	19	19	19	20	19	20	20
Rochusbuurt	10	10	10	10	10	9	9	8	8	8	8	8	8	8	8	8	8	9	9	9	9	9	9	10
Elzent-Noord	9	9	9	9	9	9	9	9	11	12	12	11	11	11	11	11	10	9	9	9	9	9	9	9
Tuindorp	21	21	21	21	21	20	19	16	14	14	13	14	15	13	13	14	15	18	18	19	19	19	20	21
Joriskwartier	9	9	9	9	9	9	8	7	7	7	7	7	7	7	7	7	7	8	9	9	9	9	9	9
Bloemenplein	9	9	9	9	9	9	9	8	9	9	10	9	9	10	10	9	9	9	9	9	9	9	9	9
Looiakkers	4	5	5	5	5	4	4	4	5	5	5	5	5	5	5	5	4	4	4	4	4	4	4	4
Elzent-Zuid	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Kerstroosplein	15	15	15	15	15	15	13	11	10	10	10	10	11	10	10	10	11	13	14	14	14	14	14	15
Gerardusplein	23	23	23	23	23	22	21	18	17	17	16	16	17	16	16	16	17	20	21	21	22	22	22	23
Genneperzijde	10	10	10	10	10	10	9	9	10	10	10	9	10	9	9	9	9	9	9	9	9	9	9	10
Roosten	8	8	8	8	8	7	7	6	5	5	4	4	5	4	4	5	5	6	7	7	7	7	7	7
Eikenburg	14	14	14	14	14	13	13	11	10	10	10	10	10	9	9	10	10	12	12	13	13	13	13	14
Sportpark Aalsterweg	0	0	0	0	0	1	1	2	3	3	4	3	3	4	3	3	2	1	1	1	1	1	1	0
Puttense Dreef	11	11	12	12	11	11	10	8	7	7	6	7	7	6	6	7	7	9	10	10	10	11	11	11
Poeijers	5	5	4	4	5	6	9	16	28	29	31	29	26	30	29	26	19	11	7	7	7	6	6	5
Burghplan	23	24	24	24	24	23	21	18	16	16	15	16	17	15	15	16	17	20	21	21	22	22	22	23
Sintenbuurt	15	15	15	15	15	14	13	11	10	10	9	9	10	9	9	10	10	12	13	13	14	14	14	15

Tivoli	12	12	12	12	12	11	10	8	7	7	6	7	7	6	6	7	7	9	10	10	11	11	11	11
Gijzenrooi	20	20	20	20	20	20	18	15	12	12	11	11	13	11	11	12	13	16	18	18	19	19	19	20
Nieuwe Erven	8	8	8	8	8	8	8	7	7	7	7	7	7	7	7	7	7	7	8	8	8	8	8	8
Kruidenbuurt	22	23	23	23	23	22	20	16	14	14	13	13	14	12	12	14	15	18	20	20	21	21	21	22
Schuttersbosch	6	6	6	6	6	6	5	4	4	3	3	3	4	3	3	3	4	5	5	5	5	5	6	6
Leenderheide	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Riel	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
Villapark	18	18	18	18	18	18	17	18	20	21	21	20	20	20	20	20	18	17	17	17	17	17	17	18
Lakerlopen	24	24	24	24	24	24	23	23	25	29	32	30	29	31	33	28	25	25	26	24	25	23	23	24
Doornakkers-West	29	29	29	29	29	28	27	24	23	23	22	22	23	21	21	22	22	25	26	27	27	27	28	29
Doornakkers-Oost	21	22	22	22	22	21	19	17	15	15	14	14	15	14	14	15	15	18	19	20	20	20	20	21
Tongelresche Akkers	7	7	7	7	7	7	6	5	5	5	4	5	5	4	4	5	5	6	6	6	6	6	7	7
Muschberg	36	37	37	37	37	35	32	27	23	23	21	22	24	21	21	23	24	30	32	33	34	34	35	36
Urkhoven	2	2	2	2	2	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
't Hofke	30	31	31	31	31	30	27	23	20	20	19	20	21	19	19	20	21	26	27	28	28	28	29	30
Karpen	7	7	7	7	7	7	6	5	4	4	4	4	5	4	4	4	5	6	6	6	6	6	7	7
Koudenhoven	6	7	7	7	7	6	6	5	4	4	4	4	4	4	4	4	4	5	6	6	6	6	6	6
Limbeek-Zuid	9	9	9	9	9	9	8	7	7	7	7	7	7	6	6	7	7	8	8	8	8	9	9	9
Limbeek-Noord	16	16	16	16	16	16	15	13	12	13	13	13	13	13	13	13	13	14	15	15	15	15	15	16
Hemelrijken	20	20	20	20	20	20	20	20	22	24	25	24	23	24	25	23	21	20	20	20	20	20	20	20
Gildebuurt	13	13	13	13	13	13	12	12	13	15	16	15	15	16	16	14	13	13	14	13	13	13	13	13
Woenselse Waterm.	11	11	11	11	11	11	10	10	12	12	12	11	11	11	11	11	10	10	10	10	10	10	10	11
Woensel-West	28	29	29	29	29	28	27	26	27	28	28	27	27	27	27	27	25	26	26	27	27	27	27	28
Kronehoef	31	31	31	31	31	30	29	26	26	26	25	25	26	25	24	25	25	27	28	29	29	29	30	31
Barrier	18	18	18	18	18	17	16	13	11	11	10	10	11	10	10	11	12	15	15	16	16	16	17	17
Mensfort	27	27	27	27	27	26	24	20	18	18	17	17	19	16	17	18	19	23	24	24	25	25	26	27
Rapenland	23	23	23	23	23	24	26	31	41	42	44	42	40	43	42	39	33	27	24	24	25	24	24	24
Vredeoord	0	0	0	0	0	1	2	4	8	9	10	9	8	9	9	8	6	2	1	1	1	1	1	0
Generalenbuurt	47	48	48	48	48	46	43	36	32	32	30	31	33	29	29	32	33	40	42	43	44	44	45	47

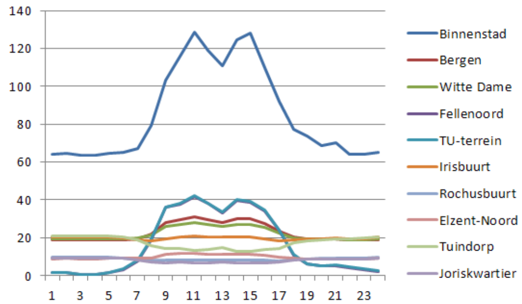
Oude Toren	14	14	14	14	14	14	13	10	9	9	8	8	9	8	8	8	9	12	12	13	13	13	13	14
Hondsheuvels	2	2	2	2	2	2	3	6	11	11	12	11	10	11	11	10	7	4	3	3	3	3	2	2
Oude Gracht-West	27	27	27	27	27	26	24	20	18	19	18	18	19	17	17	18	19	23	24	24	25	25	25	26
Oude Gracht-Oost	15	15	15	15	15	14	14	13	13	13	13	13	13	12	12	13	12	13	13	14	14	14	14	15
Eckartdal	0	0	0	0	0	0	1	2	4	4	5	4	4	4	4	4	3	1	1	1	1	0	0	0
Driehoeksbos	12	12	12	12	12	12	11	11	13	13	13	13	13	13	13	13	11	11	11	11	11	11	11	12
Prinsejagt	41	41	41	41	41	40	36	30	25	25	23	24	26	22	22	24	27	34	36	37	38	38	39	40
Jagershoef	29	29	29	29	29	28	26	21	18	18	16	17	19	16	16	17	19	24	25	26	27	27	27	28
't Hool	17	17	17	17	17	16	15	12	10	10	9	9	10	9	9	10	11	14	15	15	16	16	16	17
Winkelcentrum	7	7	7	7	7	7	8	11	16	20	23	21	19	23	24	19	15	11	10	9	9	7	7	7
Vlokhoven	29	29	30	30	29	28	26	21	18	18	17	17	19	16	16	18	19	24	26	26	27	27	28	29
Kapelbeemd	4	4	3	3	4	5	9	17	29	31	33	30	27	32	31	28	20	11	7	6	7	6	5	5
Kerkdorp Acht	41	42	42	42	42	40	37	31	27	27	25	25	28	24	24	26	28	34	36	37	38	38	39	41
Gunterslaer	40	41	41	41	41	40	38	36	38	39	39	38	39	37	37	37	35	37	37	38	39	39	39	40
Spaaihoef	50	51	51	51	51	49	45	36	30	30	27	28	32	26	26	30	32	41	44	45	46	47	48	50
Hoeven	41	41	41	41	41	40	36	30	25	25	23	24	26	22	22	25	27	34	36	37	38	38	39	40
Woenselse Heide	50	51	51	51	51	49	46	40	37	37	35	35	38	34	34	36	37	43	45	46	47	48	48	50
Tempel	49	49	49	49	49	47	44	39	37	39	38	38	39	37	37	38	38	43	45	45	46	46	47	48
Blixembosch-West	22	23	23	23	23	22	20	16	14	13	12	13	14	12	12	13	15	18	20	20	21	21	21	22
Blixembosch-Oost	66	66	67	67	66	64	58	48	41	41	38	39	43	37	37	40	43	54	58	59	61	61	62	65
Castiliëlaan	1	1	1	1	1	1	2	4	8	8	9	8	7	9	8	7	5	3	2	1	1	1	1	1
Eckart	36	37	37	37	37	35	33	27	24	24	22	23	25	22	22	23	25	30	32	33	34	34	35	36
Luytelaer	12	12	12	12	12	11	10	8	7	7	6	6	7	6	6	7	7	9	10	10	11	11	11	11
Vaartbroek	47	47	48	48	47	46	42	34	29	29	27	28	31	26	26	29	31	39	41	43	43	44	45	46
Heesterakker	29	29	29	29	29	28	25	21	17	17	16	16	18	15	15	17	19	23	25	26	26	27	27	28
Esp	2	2	2	2	2	2	3	5	9	10	10	9	9	10	10	9	6	4	3	3	3	2	2	2
Bokt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Eliasterrein,	23	23	23	23	23	22	21	17	15	15	14	15	16	14	14	15	16	19	20	21	21	22	22	23
Philipsdorp	16	16	16	16	16	16	16	15	16	17	18	17	17	17	17	16	15	16	16	16	16	16	16	16

Engelsbergen	8	8	8	8	8	8	8	8	8	9	9	9	9	9	9	8	8	8	8	8	8	8	8	8
Schouwbroek	13	13	13	13	13	13	12	10	9	10	9	9	10	9	9	9	10	11	12	12	12	12	13	13
Schoot	21	21	21	21	21	20	19	18	18	19	19	18	19	18	18	18	18	19	19	19	20	20	20	21
Strijp S	1	1	1	1	1	1	1	2	4	5	5	5	4	5	5	4	3	2	1	1	1	1	1	1
Hurk	12	12	10	10	12	14	20	36	61	66	74	67	60	71	71	61	45	26	20	18	18	15	14	13
Het Ven	32	33	33	33	33	32	30	27	27	28	27	27	28	27	27	27	26	29	30	30	31	31	31	32
Lievendaal	27	27	28	28	27	27	25	22	21	22	21	21	22	20	20	21	21	24	25	25	26	26	26	27
Drents Dorp	17	17	17	17	17	17	16	14	14	14	14	14	14	13	13	14	14	15	15	16	16	16	16	17
Zwaanstraat	0	0	0	0	0	0	1	2	3	3	3	3	3	3	3	3	2	1	1	1	1	0	0	0
Wielewaal	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1
Herdgang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mispelhoef	3	3	3	3	3	4	7	13	22	23	25	23	21	24	24	21	15	8	6	5	5	5	4	4
BeA2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Meerbos	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Grasrijk	42	43	43	43	43	41	37	31	26	26	24	25	27	23	23	26	28	35	37	38	39	39	40	42
Zandrijk	28	28	29	29	28	27	25	20	17	16	15	16	17	14	14	16	18	23	25	25	26	26	27	28
Waterrijk	8	8	8	8	8	8	7	6	5	5	4	5	5	4	4	5	5	6	7	7	7	7	7	8
Park Forum	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
Flight Forum	5	5	4	4	5	7	12	23	40	42	45	42	37	43	42	38	27	14	10	9	9	8	7	6
Eindhoven Airport	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Bosrijk	4	4	4	4	4	4	3	3	3	3	2	2	3	2	2	3	3	3	3	3	4	4	4	4
Meerrijk	0	0	0	0	0	0	0	1	1	2	3	2	2	3	3	2	1	1	1	0	0	0	0	0
Schrijversbuurt	27	27	27	27	27	26	24	21	21	21	20	20	21	20	20	20	20	23	24	25	25	25	25	26
Oude Spoorbaan	15	15	15	15	15	15	14	13	13	13	13	13	14	13	13	13	13	14	14	14	15	14	15	15
Hagenkamp	9	9	9	9	9	9	9	9	10	11	11	10	10	10	10	10	9	9	8	9	9	9	9	9
Genderdal	22	22	22	22	22	22	21	19	19	19	18	18	19	18	17	18	18	20	20	21	21	21	21	22
Blaarthem	20	21	21	21	21	20	19	17	16	16	16	16	16	15	15	16	16	18	19	19	19	19	20	20
Rapelenburg	6	6	6	6	6	5	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6
Bennekel-Oost	25	25	25	25	25	24	22	19	17	17	16	16	17	15	16	17	17	21	22	23	23	23	24	25

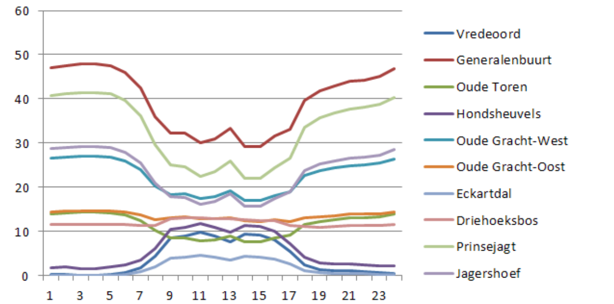
Bennekel-West,	26	26	27	27	26	25	23	19	17	17	15	16	17	15	15	16	18	22	23	24	24	24	25	26
Gennep	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Beemden	1	1	0	0	1	3	7	16	31	32	36	32	28	34	33	29	20	9	5	4	4	3	3	2
Genderbeemd	35	35	35	35	35	34	32	28	26	26	25	25	27	24	24	26	26	30	31	32	33	33	33	34
Hanevoet	34	34	34	34	34	33	30	25	23	23	22	22	24	21	21	23	24	29	30	31	31	31	32	33
Ooievaarsnest	10	10	10	10	10	10	9	7	6	6	5	6	6	5	5	6	7	8	9	9	9	9	10	10
Totaal	1.980	2.000	2.000	2.000	2.000	1.960	1.880	1.780	1.880	1.940	1.940	1.900	1.920	1.880	1.880	1.860	1.760	1.840	1.860	1.880	1.920	1.900	1.920	1.980

Electric vehicles per neighbourhood for every hour of the day

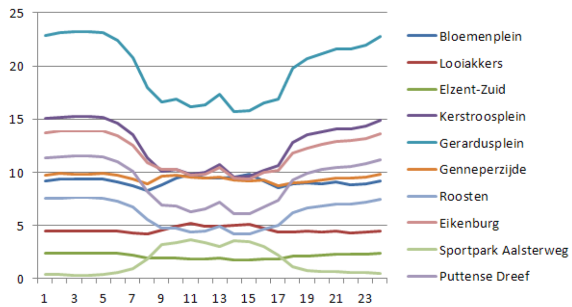
Appendix J



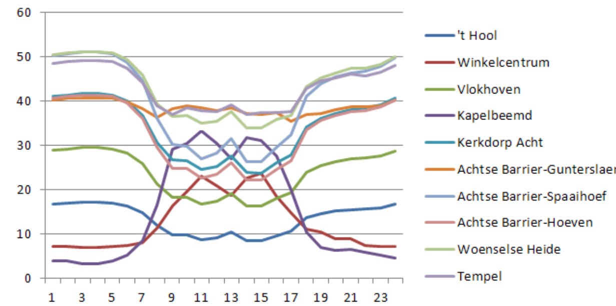
Binnenstad
Bergen
Witte Dame
Fellenoord
TU-terrein
Irisbuurt
Rochusbuurt
Elzent-Noord
Tuindorp
Joriskwartier



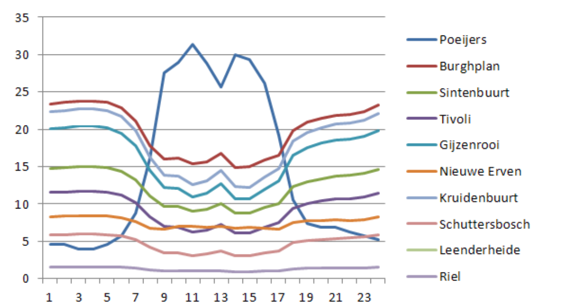
Vredeoord
Generalenbuurt
Oude Toren
Hondsheuvels
Oude Gracht-West
Oude Gracht-Oost
Eckartdal
Driehoeksbos
Prinsejagt
Jagershoef



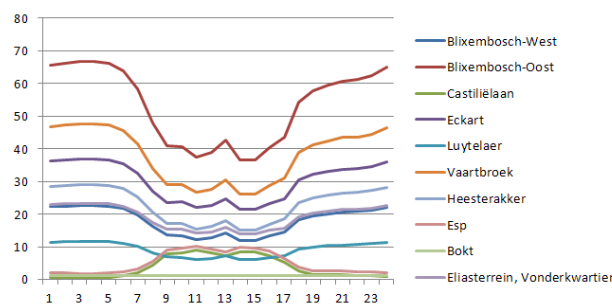
Bloemenplein
Looiakkers
Elzent-Zuid
Kerstroosplein
Gerarduspiein
Genneperzijde
Roosten
Eikenburg
Sportpark Aalsterweg
Puttense Dreef



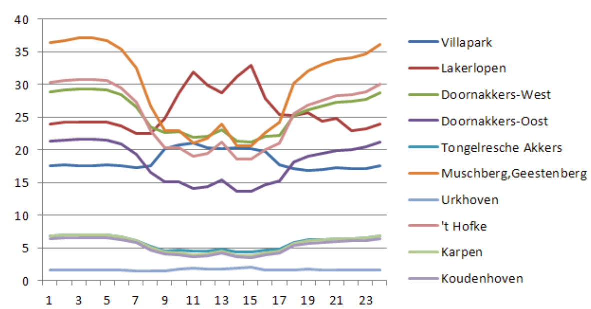
't Hool
Winkelcentrum
Vlokhoven
Kapelbeemd
Kerkdorp Acht
Achtse Barrier-Gunterslaer
Achtse Barrier-Spaaihoef
Achtse Barrier-Hoeven
Woenselse Heide
Tempel



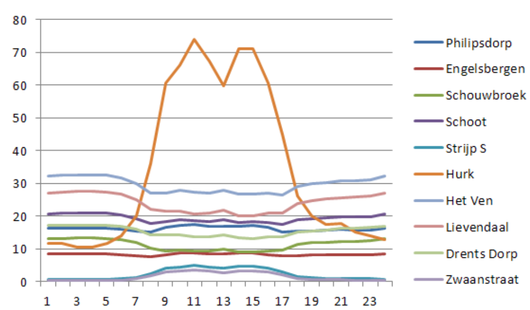
Poeijers
Burghplan
Sintenbuurt
Tivoli
Gijzenrooi
Nieuwe Erven
Kruidenbuurt
Schuttersbosch
Leenderheide
Riel



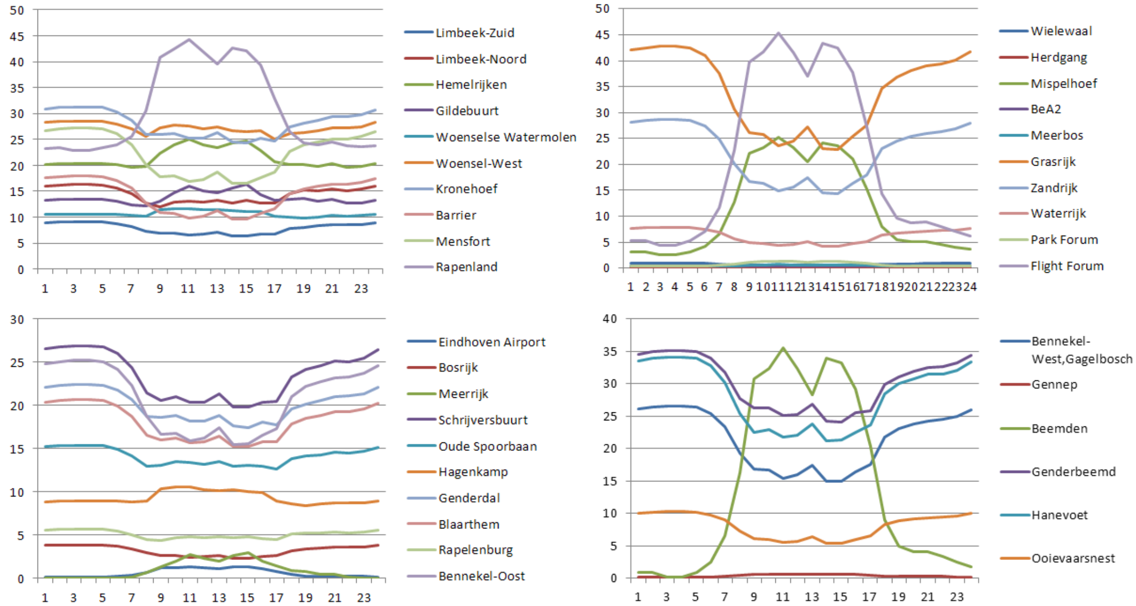
Blixembosch-West
Blixembosch-Oost
Castiliëlaan
Eckart
Luytelaer
Vaartbroek
Heesterakker
Esp
Bokt
Eliasterrein, Vonderkwartier



Villapark
Lakerlopen
Doornakkers-West
Doornakkers-Oost
Tongelresche Akkers
Muschberg,Geestenberg
Urkhoven
't Hofke
Karpen
Koudenhoven



Philipsdorp
Engelsbergen
Schouwbroek
Schoot
Strijp S
Hurk
Het Ven
Lievendaal
Drents Dorp
Zwaanstraat



Fluctuations in numbers of electric vehicles per neighbourhood over the course of a day

Appendix K

Neighbourhoods	Electric vehicles
Binnenstad	105
Bergen	27
Witte Dame	22
Fellenoord	30
TU-terrein	30
Irisbuurt	20
Rochusbuurt	9
Elzent-Noord	10
Tuindorp	17
Joriskwartier	8
Bloemenplein	9
Looiakkers	5
Elzent-Zuid	2
Kerstroosplein	13
Gerardusplein	20
Genneperzijde	9
Roosten	6
Eikenburg	12
Sportpark Aalsterweg	3
Puttense Dreef	11
Poeijers	23
Burghplan	20
Sintenbuurt	12
Tivoli	11
Gijzenrooi	19
Nieuwe Erven	8
Kruidenbuurt	18
Schuttersbosch	6
Leenderheide	0
Riel	1
Villapark	18
Lakerlopen	26
Doornakkers-West	26
Doornakkers-Oost	18
Tongelresche Akkers	6
Muschberg,Geestenberg	30
Urkhoven	2
't Hofke	25
Karpen	6
Koudenhoven	5
Limbeek-Zuid	8
Limbeek-Noord	14

Hemelrijken	21
Gildebuurt	14
Woenselse Watermolen	11
Woensel-West	27
Kronehoef	28
Barrier	14
Mensfort	22
Rapenland	37
Vredeoord	7
Generalenbuurt	40
Oude Toren	14
Hondsheuvels	9
Oude Gracht-West	22
Oude Gracht-Oost	14
Eckartdal	3
Driehoeksbos	12
Prinsejagt	39
Jagershoef	23
't Hool	16
Winkelcentrum	18
Vlokhoven	24
Kapelbeemd	25
Kerkdorp Acht	34
Achtse Barrier-Gunterslaer	39
Achtse Barrier-Spaaihoef	49
Achtse Barrier-Hoeven	33
Woenselse Heide	43
Tempel	43
Blixembosch-West	22
Blixembosch-Oost	53
Castiliëlaan	7
Eckart	30
Luytelaer	11
Vaartbroek	38
Heesterakker	28
Esp	8
Bokt	1
Eliasterrein, Vonderkwartier	19
Philipsdorp	16
Engelsbergen	8
Schouwbroek	11
Schoot	19
Strijp S	4
Hurk	55
Het Ven	30

Lievendaal	24
Drents Dorp	15
Zwaanstraat	3
Wielewaal	1
Herdgang	0
Mispelhoef	19
BeA2	0
Meerbos	1
Grasrijk	34
Zandrijk	27
Waterrijk	6
Park Forum	1
Flight Forum	34
Eindhoven Airport	1
Bosrijk	3
Meerrijk	2
Schrijversbuurt	24
Oude Spoorbaan	14
Hagenkamp	9
Genderdal	20
Blaarthem	18
Rapelenburg	5
Bennekel-Oost	21
Bennekel-West,Gagelbosch	21
Gennep	1
Beemden	26
Genderbeemd	30
Hanevoet	28
Ooievaarsnest	8
Total	**2107**

English summary

SPATIAL MODELLING TO ALLOCATE LOCATIONS FOR PUBLIC CHARGING STATIONS

Determining the locations of public charging stations for the municipality of Eindhoven

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ABSTRACT

This paper is about the development of a location allocation model for public charging stations. Especially in urban environments a public charging infrastructure is required for further developments of electric mobility. The model is applied to the municipality of Eindhoven to find a solution for the location problem of public charging stations. A scenario for the year 2020 is created to determine the settings for the model. Scenario analysis will lead to recommendations on locations and quantities of public charging stations.

Keywords: public charging infrastructure, agent-based modelling, GIS, multi-objective optimisation, scenario analysis

INTRODUCTION

The development of electric mobility and electric vehicles has increased significantly over the last couple of years. Global awareness about the impact of human activities on the environment has become much greater over the past decades. Resources such as fossil fuels are getting more scarce and pollution, especially in densely populated areas, is threatening the quality of life. Global agreements on reducing emissions have been made, targets have been set and actions have been taken to achieve environmental goals. In order to continue the process towards a cleaner and more sustainable environment, innovation is needed. Urban areas can still improve significantly to become more sustainable. New developments in the field of electric mobility will contribute to reach sustainability goals. The use of electric vehicles in urban areas will decrease carbon emissions, increase the air quality and contribute to the overall quality of life within urban areas.

The use electric vehicles largely depends on a supporting charging infrastructure for electric vehicles. Electric vehicles and a charging infrastructure are interdependent; the development of electric vehicle usage requires a supporting infrastructure and installing a charging infrastructure is only useful when a certain level of electric vehicle usage is reached. This interdependence results in a great challenge for the development of electric mobility. It is assumed that in order to disrupt this dependency circle a supportive charging infrastructure must be in place prior to the introduction of a new technology (Sovacool & Hirsh, 2009).

Research approach

It is desirable to develop a supporting infrastructure in order to stimulate the use of electric vehicles. However, the development of a public infrastructure is hampered because currently there is no profitable business case for public charging stations. Most of the developments for a public charging infrastructure are generally initiated as pilot projects by governments, network operators and research institutes. It is expected that after 2015 a profitable business plan for public charging station can be developed (PRC, 2013) and that the market for public charging services will grow from a developing market to a mature market (Innopay, 2011). A growing market for public charging services presents new challenges. This paper focuses on the spatial challenges that a growing market for public charging services entails.

The problem definition for this research is phrased as: *"An integrated approach for allocating locations for public charging stations is lacking"*. The owner of this problem is for the majority of cases a local government or municipality and the problem is most relevant to urban areas.

The objective of this paper is to create a location allocation model for public charging stations. The municipality of Eindhoven will be used as a case study to apply the model to the real world. The objective is to create solutions for the location problem of public charging stations in the municipality of Eindhoven.

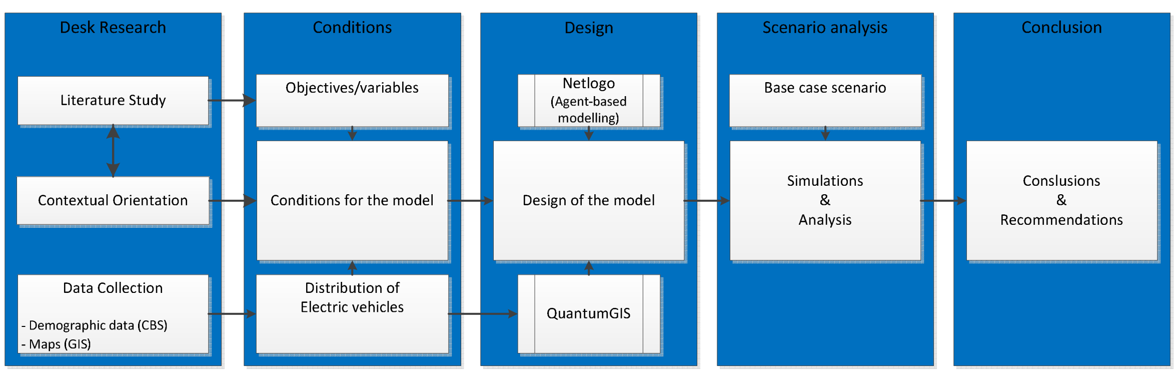

Figure 1: Research model

CONTEXTUAL ORIENTATION

Over the last couple of years, the development of electric mobility is growing rapidly. Although the global market for electric vehicles is growing, it is no guarantee for success. The development of electric mobility is facing a very mature market of conventional car manufacturers. Fortunately, existing car manufacturers are increasingly involved in the developments of electric mobility. Future developments of electric vehicles will be very important for the growth of electric mobility. Existing car manufacturers have an essential role in these developments because for the most part, they will eventually determine which electric vehicles and which technologies will enter the market. The performances and costs of batteries for electric vehicles is perceived as one of the greatest barriers for the development of electric mobility (JRC, 2010).

A distinction is made between full electric vehicles (FEV or BEV) and hybrid electric vehicles (HEV). Full electric vehicles are solely driven by batteries while hybrid electric vehicles are driven by both a combustion engine and batteries. Plug-in hybrid electric vehicles (PHEV) are hybrids which can be plugged in for recharging. Since this paper focuses on a charging infrastructure for electric vehicles it only considers full electric vehicles and plug-in hybrid electric vehicles.

The development of electric mobility has received a lot of attention in the Netherlands and is growing steadily. The E-Laad foundation, a cooperation of Dutch network operators, has realised approximately 2.500 public charging stations in The Netherlands. Due to limited budgets and interference by the national governance, E-Laad was forced to stop the deployment of public charging stations.

FIELD OF CHARGING STATIONS

The sole purpose of a (re)charging station is obviously to replenish batteries of electric vehicles. There is a wide variety of charging stations and applications of charging stations. Besides recognising all modes and types of charging stations it is most important to acknowledge the different applications of charging stations and usage patterns. This paper will focus on publicly accessible charging station using cables and plugs for recharging, other techniques are not within the scope of this paper. Publicly accessible charging stations can be divided in public charging stations, extended private charging stations and semi-public charging stations.

To further stimulate electric vehicle usage and to increase the deployment of charging stations, standards are essential. The main purpose of standards is to ensure that electric vehicle drivers can safely and conveniently enjoy the use of both electric vehicle and charging station which increases user acceptance and decrease costs (ACEA, 2012). The current business case for operating a public charging station has a financial gap. For a profitable business case local and national governments can actively facilitate operators by reducing costs for leaseholds, permits and applications. Network operators also play a crucial role in creating a profitable business case by reducing costs for the connection to the grid. Economies of scale and more sales of energy will also contribute to the viability of the business case.

Both charging stations and electric vehicles come along with certain limitations, which have to be dealt with now and in the future. The (re)charging speed is determined by the capabilities of both charging station *and* electric vehicle. For electric vehicles the on-board charger determines the charging power of the vehicle. Charging station themselves also have limitations regarding efficiency in terms of utilisation. The practical capacity of a station will be significantly less than the theoretical output of the station because in practice the charging station will not be utilised 24 hours a day.

Matching electric vehicle usage patterns with types of charging stations will also stimulate the future development of a charging infrastructure. The “charging tree” (Ladder van Laden) presented by the Dutch Ministry of Economic Affairs and the Taskforce Formule E-Team is a guideline for the implementation of a charging infrastructure and matches the use of stations with types by prioritising the types of charging stations.

METHODS

For this research several research methods are used which are also shown in the research model. The used research methods are multi-objective optimisation, GIS, agent-based modelling and scenario analysis.

Multi-objective optimisation

With multi-objective optimisation a trade-off between divergent objectives exists which results in a number of solutions. If one solution is better in terms of one objective, it comes only from a sacrifice off other objectives because the objectives are not independent (Deb, 2005). The aim of multi objective optimisation is not to solve a single objective or to find an optimal solution corresponding to each objective function (Deb, 2005).

GIS

Geographic information systems (GIS) are used to gather, analyse, modify, manage and present all types of spatial information. GIS is an operational and supporting information system where data can be related to a specific location or area. Combining data with geographic information such as maps, results in numerous forms of output. With GIS many products can be created such as maps, charts, tables and graphs. GIS is commonly used in planning, analysis of traffic, transport, environment, safety, earth sciences and many more applications.

Agent-based modelling

Agent-based modelling is a simulation technique for modelling complex systems. An agent-based model generally has three elements; a set of agents with attributes and behaviours, a set of relationships and methods of interaction and the agents’ environment (Macal, 2010). The systems are modelled as a collection entities called agents. The main benefits of agent-based modelling is that is captures emergent phenomena, provides a natural description of a system and it is flexible (Bonabeau, 2002).

Scenario analysis

The use of scenarios stimulates strategic thinking and helps to overcome thinking limitations by creating multiple futures (Amer, 2012). Scenarios can be described as: “a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points” (Kahn, 2000). Scenarios can also be defined as a description of a future situation and the course of events which allows one to move forward from the actual to the future situation. Scenario development creates a better understanding of plausible future developments by looking at trends on a macro level such as: socio-cultural, technological, ecological, political and economic developments. All the above described method will be used to develop a location allocation model for public charging stations. Agent-based modelling and GIS will be integrated to design the model while multi-objective optimisation is used to determine the decision space of the model.

OBJECTIVES & VARIABLES

A subset of two conflicting objectives based on reliability, availability, maintainability and costs (RAM&S) are taken into account; availability and costs or profitability. The objectives together with the constraints for the objectives will determine the decision space of the model.

Availability

The first objective for the model is to maximise availability $A(x)$. Among others, the availability of a public charging station determines the usefulness of a station. The availability of a charging station is determined by demand and supply; high supply and low demand will result in a high availability. The objective function for daily availability is:

$$f(x) = A(x) = supply - demand$$

The demand is determined by the charging output in kW and the effective charging time which is the assumed maximal capacity of charging station in practice. The demand for a station is determined by the energy consumption per vehicle and the number of vehicle within the surrounding of a stations. The constraint for availability is determined by the relation between demand and supply. If demand exceeds supply, a station will be overloaded which decreases the availability dramatically. When demand exceeds supply a station is more likely to be occupied which is not desirable for users in need of charging. The limit for the objective space is reached when demand exceeds supply. The constraint $g(x)$ for the availability objective is:

$$g(x) = Demand \leq Supply$$

Profitability

The second objective for the model is to maximise profitability. Currently, public charging stations do not have a profitable business case but for the development of a charging infrastructure a profitable business plan for public charging stations is essential. The profitability of a station depends on several variables such as the initial investment, interest rates, profits per kWh and utilisation. The latter is one of the most important variables because the utilisation almost directly determines the profitability of a charging station. For a charging station to be profitable the actual daily utilisation has to be higher than the required daily utilisation for profitability. The objective function for the actual daily utilisation $U_a(x)$ is:

$$f(x) = U_a(x) = \text{Actual daily utilisation}$$

The actual daily utilisation in hours is determined by the energy consumption per vehicle and the number of vehicle within the surrounding of a stations divided by the charging output of a station in kW. The actual daily utilisation has to be higher or equal to the minimal required utilisation for a station to be profitable.

$$U_a(x) \geq U_r(x)$$

The daily required utilisation (hrs) is determined by calculating the necessary hours of utilisation per day for generating the desired profitability. The most important variables used to calculate these hours are initial investment costs, desired rate of return on investment, selling and purchasing prices for electricity, and the charging output of a station.

Decision space

The above described objectives are divergent, meaning that if one solution is better in terms of one objective, it comes only from a sacrifice off the other objectives (Deb, 2005). Therefore the aim is not to find an optimal solution to each of the objective but to find an optimum compromise solution between the objectives. The two objectives combined, determine the decision space for the location allocation model.

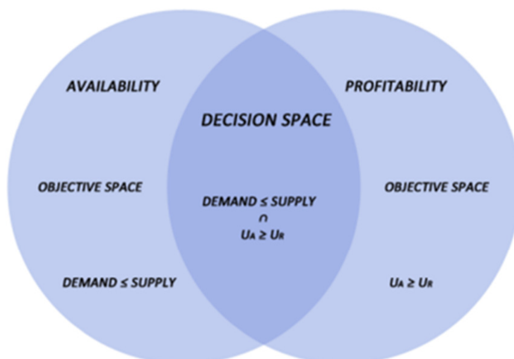

Figure 2: Decision space

LOCATION PROBLEM

In facility location problems, a facility agent deals with the problem of finding a location that provides services for a spatially distributed demand. Location allocation models, which deal with facility location problems, intend to find a spatial distribution of facilities that maximises or optimises objective functions within one or more constraints (Arentze, 2010). A distinction is made between two different location problems; median problems and covering problems. Median problems measure the effectiveness of a facility location by determining the average distance by those who visit it while covering problems regard a demand as covered when it can be served within a specific time or distance from a facility. Within covering problems set covering problems set out to cover all demand and maximal covering problems use given number of facilities to maximise the demand covered.

The location problem considered for the model is neither exactly aligned with the definition of a median problem nor with the definition of a covering problem. For the model the maximum walking distance from destination to vehicle or charging station is considered to be a crucial factor determining whether a charging station will be used. If a destination is outside the catchment area of a charging station it is assumed that the destination is not covered and that the station will not be utilised.

The location problem for the model can be described as a multi-objective partial covering problem. The problem is multi-objective because it has to deal with two conflicting objectives. Furthermore, the problem is not a set covering problem but a partial covering problem because it does not cover all demand but only the demand within the decision space of the objectives.

ENVIRONMENT

The environment for the model will be determined by a distribution of electric vehicle within the study area. The study area for the model is the municipality of Eindhoven. The distribution of electric vehicles within the study area is based on a forecast of electric vehicles in Eindhoven in the year 2020. Based on the national objectives for electric vehicles in 2020, the national growth of car ownership and the proportion of represented cars in Eindhoven the number of electric vehicles in Eindhoven is assumed to be 2.000 by 2020. As mentioned before with electric vehicles only FEV and PHEV are considered. According to the function living, working and visiting three distributions are created for all 2.000 vehicles at neighbourhood level. For the three distributions the electric vehicles per neighbourhood are in proportion with the number of cars owned, the number of workplaces and the total floor area for sales.

The number of electric vehicles per neighbourhood, regardless for which function, will change over time because vehicles are used for transportation and the movements over the course of a day cannot be ignored. For the locations of electric vehicles during a day a distinction is made between at home, at work, at facilities and electric vehicles which are travelling. The three distributions per function and the movement of electric vehicles over the course of a day are combined to create snapshots of distribution for every hour of the day. With these 24 snapshots the movement of electric vehicles during a day is illustrated.

A final distribution is needed because in the real world charging stations are static and the model needs one distribution on which the locations of charging station can be determined. for all neighbourhoods presenting a substantial higher or lower amount of electric vehicles between the average number of electric vehicle during these periods is used. In other words, for all neighbourhoods that show a substantially higher or lower number of electric vehicles over a period of time, the averages of this period is used for a final distribution. For all the other neighbourhoods which show no substantial difference the average of electric vehicles over all 24 hours is used for a final distribution.

DESIGN OF THE MODEL

The model is designed with the program Netlogo. Netlogo is a programmable modelling environment for simulating natural and social phenomena, it is a relatively simple system but well suited for modelling complex systems.

The model has two buttons to run a simulation; the setup button and the go button. When the setup button is used the model responds by (re)setting the model to the initial state. The setup button also clears all previous settings and simulations. When the go button is pressed a simulation starts and charging stations will appear. When a simulation is run the algorithm first uses the minimum catchment area of a station and swaps all cells to determine if a location is in the decision space using. When no more locations can be found the maximum catchment area is used and again all cells are swapped to determine if a location is within the decision space. When no more locations can be allocated the simulation stops.

The interface which is shown below, is used operate the location allocation model and it shows all the buttons, sliders and monitors for running simulations. Besides these elements it also has a view which shows the map of Eindhoven and the locations of the charging stations. The monitors which are coloured beige, display the number of electric vehicles, charging stations and the number of electric vehicles which are covered or serviced by a station. The last monitor displays the average number of covered electric vehicles per charging station. The sliders in the interface are coloured green and they represent the variables mentioned in chapter 5. The user of the location allocation model can set the variables to the preferred or expected values. By altering the values of the variables the decision space of the model will be altered accordingly.

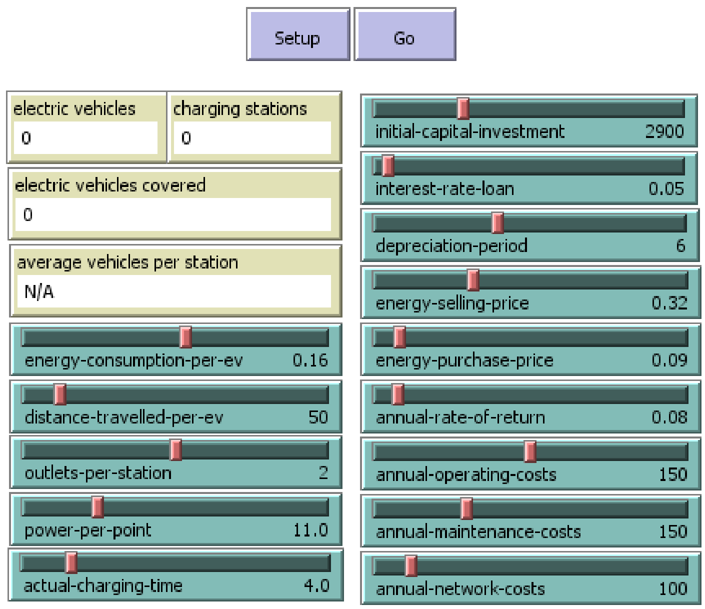

Figure 3: Interface of the model

SCENARIO ANALYSIS

The scenario created to determine the values for the variables in the model is a base case scenario. The scenario will present an outlook for the year 2020 and the general assumption for this scenario is moderate growth of electric mobility in The Netherlands. It is assumed that the average electric vehicle is no longer limited to 3,7 kW charging but that the average charging capacity of electric vehicles will be 11 kW. On the charging infrastructures side, it is assumed that the types and techniques used for charging stations in 2020 are comparable with the charging stations used by E-laad. Communications between electric vehicle drivers and charging stations have also not improved significantly meaning that the efficiency of charging stations will remain relatively low.

To find a solution for the location problem the model is used to analyse the base case scenario. In total ten random distributions of electric vehicles are created and for every random distribution twelve simulations are run with the model, which resulted in 120 simulations. All of these simulations present a solution to the problem but with the use of different criteria final solutions are selected. The used criteria are maximal facilitation, maximal profitability, maximal availability and minimal amount of charging stations. In total three solutions can be identified because the criteria minimal amount of charging stations and maximal profitability result in the same solutions.

CONCLUSION

The simulations run with the model provide a set of solutions for the location problem. It must be realised that the solutions provided by the model are not ultimate solutions to the problem. The model itself and the scenario analysis do not use exhaustive calculations to find the ultimate solution. Instead near optimal solutions are provided by the model. To analyse the set of solutions different criteria are used. According to each criteria a different solution can be selected from the total set of solutions which is shown in table 1. The table reveals that the criteria maximal profitability and minimal charging stations result in the same solution, this can be explained because profitability is determined by high utilisation which implies a minimal amount of charging stations covering a maximal amount of electric vehicles. In terms of electric vehicles serviced, all solutions are relatively close to each other. However when considering the amount of charging stations for every solution, the differences are substantial. Especially when the number of charging stations are expressed in cost. In the base case scenario it is assumed that the initial investment costs for realising a single public charging station is € 2900,-.

	Maximal facilitation	Maximal profitability	Maximal availability	Minimal charging stations
Charging stations	724	687	741	687
Ev's serviced	1.995	1.963	1.974	1.963
EV's/station	2,756	2,857	2,664	2,857

Table 1: Solutions according to criteria

Since municipalities are in most cases the owners of the location problem, they can use this model to gather information about how many charging station are needed and where to place them. The outcomes of this model do not specify precise locations for charging stations at street level. On a micro level the exact location of public charging station still has to be determined which depends on the policy of a municipality.

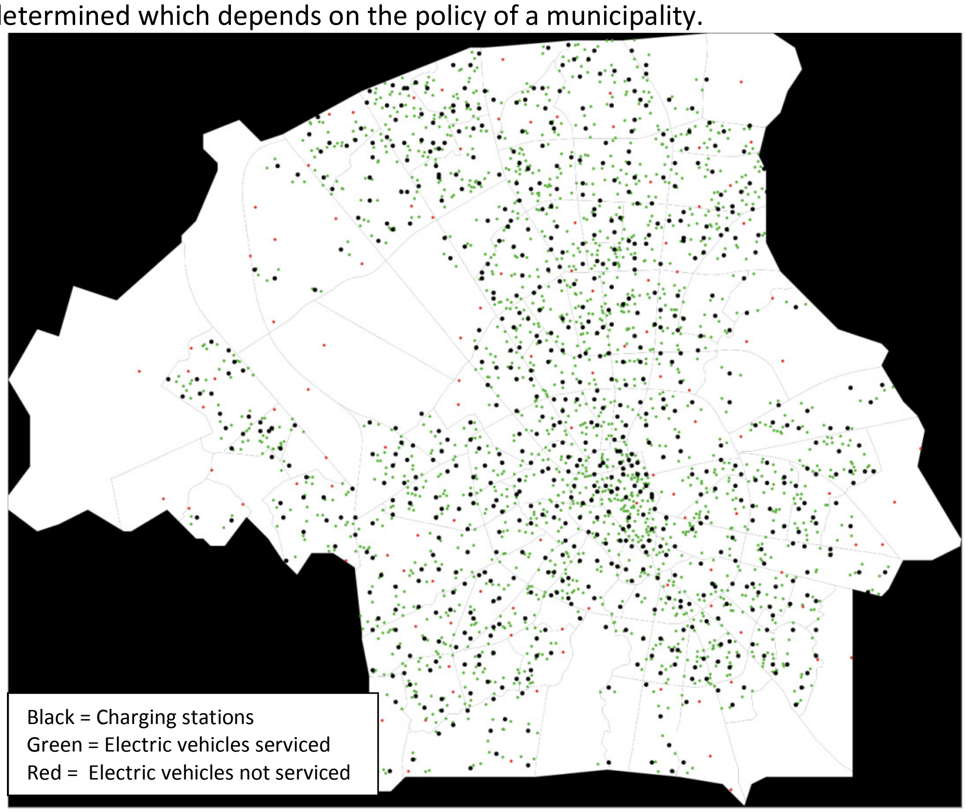

Figure 4: Map with charging station for maximum facilitation

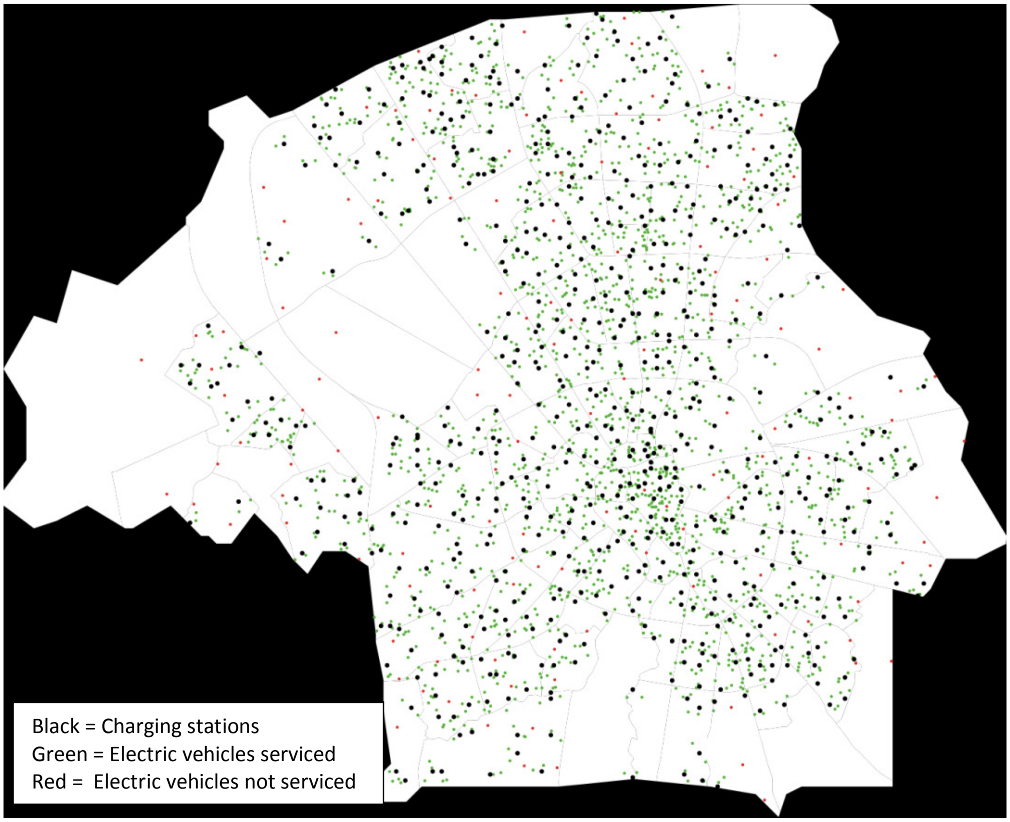

Figure 5: Map with charging stations for maximum profitability & minimal charging stations

Figure 6: Map with charging station for maximum availability

FURTHER RESEARCH

For further research it is recommended to refine the model. First of all the location is defined as a partial covering problem but instead it could also be defined as a maximal covering problem. In case of a maximal covering problem the number of public charging stations is known upfront and the model will allocate location to achieve maximal coverage. If the model is constructed like this it is more suitable when the amount of public charging stations to be created is limited. Secondly, the current model does not use distances between electric vehicles and a station directly. The only way distances are used is by setting the maximum radius of a charging station. The distances between vehicles and station could be incorporated in the model. With the use of average distances the model would solve a median problem or a combination between a median and a covering problem. Thirdly, the location problem is approached as a static problem. This is obviously true because both parked vehicles and charging stations are static but vehicles can also be considered as dynamic elements in a model. This will transform a static problem into a dynamic problem which has dramatic consequences for the construction of the model. This approach will include flows of electric vehicles and queuing components. Especially for fast charging stations this approach might be very interesting because in most cases they are situated along major exit roads or high ways.

The created environment in GIS can contain more details and in Netlogo candidate locations can be indicated. This way policies can be integrated in the model because in most cases policies of municipalities provide information about locations for charging stations at street level.

Furthermore it is extremely important to monitor the developments of electric mobility very closely. The future of electric vehicles is unknown and even within the relatively short period of this graduation projects radical changes within the field of electric mobility have occurred. The field of electric mobility offers great challenges but also changes. It is recommended to respond to these changes adequately and effectively. For now, electric mobility is still growing and perhaps the electric vehicles in our streets will be the standard instead of the exception in 2020.

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Dutch summary

RUIMTELIJKE MODELLEREN VOOR HET TOEWIJZEN VAN LOCATIES VOOR PUBLIEKE LAADPUNTEN
Het bepalen van locaties voor publieke laadpunten voor de gemeente Eindhoven
Auteursnaam: G.F. (Geert) Kanters

Masteropleiding:
Construction Management & Urban Development 2012-2013

Afstudeercommissie:
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Afstudeerdatum:
27-08-2013

SAMENVATTING INHOUD

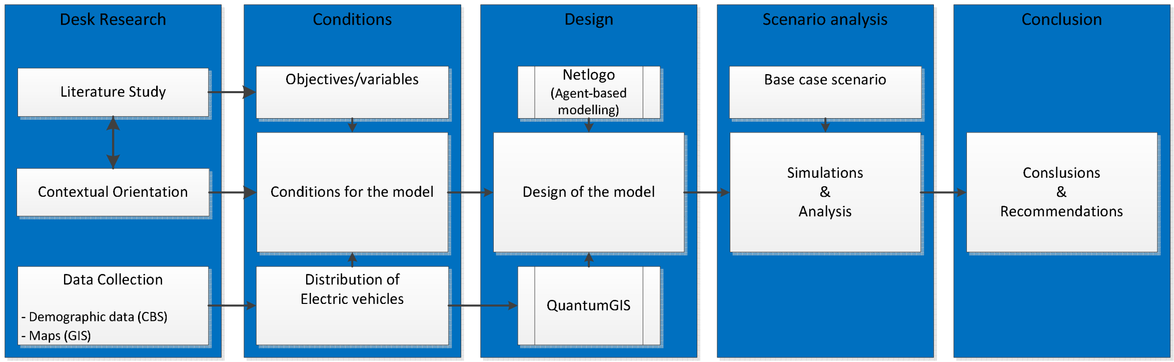
Dit artikel gaat over het ontwikkelen van een locatie toewijzingsmode voor publieke laadpunten. Vooral in een stedelijke omgeving is de aanwezigheid van een publieke laadinfrastructuur vereist voor een verdere ontwikkeling van elektrisch rijden. Het model dat in dit artikel beschreven wordt is toegepast op de gemeente Eindhoven om een antwoord te vinden op de vraag waar en hoeveel laadpunten gerealiseerd dienen te worden naar gelang een vooraf bepaald scenario. Voor het jaar 2020 is een basis scenario ontwikkeld om voor alle variabelen in het model de waarden te kunnen bepalen. Door middel van een scenarioanalyse waarbij gebruik wordt gemaakt van het model en simulaties kunnen aanbevelingen worden gedaan voor het aantal en de locaties van publieke oplaadpunten

Trefwoorden: publieke oplaadpunten, agent-based modelling, geografische informatiesystemen, multi-objective optimisation, scenario analyse.

INTRODUCTIE

De ontwikkelingen op het gebied van elektrisch rijden volgen zich in razend tempo op. De verkoop van elektrische voertuigen is de afgelopen jaren beduidend gestegen en de verwachting is dat deze markt zal blijven groeien. Omdat het aantal elektrisch voertuigen toeneemt, neemt daarmee ook de behoefte aan laadpunten toe. De groei van elektrisch vervoer is afhankelijk van een ondersteunende laadinfrastructuur. Hetgeen resulteert in een kip-ei-probleem want zonder laadinfrastructuur geen elektrische voertuigen en zonder elektrische voertuigen is er geen behoefte aan een laadinfrastructuur. Deze onderlinge afhankelijkheid kan doorbroken worden door een ondersteunende infrastructuur te realiseren voorafgaand aan de introductie van een nieuwe technologie (Hirsh, 2009).

Een groeiende markt voor elektrisch rijden brengt echter ook ruimtelijke uitdagingen met zich mee. Het probleem waar dit onderzoek zich op richt is het ontbreken van een geïntegreerde aanpak voor het toewijzen van locaties voor publieke laadpunten. In veel gevallen is de gemeente de eigenaar van dit probleem omdat doorgaans publieke laadpunten in de openbare ruimte worden geplaatst. Het doel van dit onderzoek is om een model te ontwikkelen waarmee locaties voor publieke laadpunten kunnen worden bepaald. De gemeente Eindhoven is gebruikt om het model daadwerkelijk toe te passen. Het onderzoek model met de gebruikte methoden is hieronder weergegeven.



Figuur 16: Onderzoek model

LAADPUNTEN

Er is een grote verscheidenheid aan laadpunten en laadtechnieken. Dit onderzoek richt zich op laadpunten die gebruik maken van een kabel met stekker om een elektrisch voertuig op te laden. Bovendien gaat het om laadpunten die openbaar toegankelijk zijn waaronder publieke, semipublieke en verlengd private laadpunten worden verstaan. Het Ministerie van Economische Zaken heeft in samenwerking met het Formule E-team Taskforce de ladder van laden geintroduceerd. Met de ladder van laden wordt voor het realiseren van laadpunten prioriteiten gegeven aan de te onderscheiden laadpunten.

Op het gebied van elektrische voertuigen worden logischerwijs alleen voertuigen in acht genomen die in staat zijn om te herladen door middel van een stekker. Het gaat hierbij om volledig elektrische personenauto's en plug-in hybride elektrische personenauto's. De capaciteit waarmee kan worden geladen heeft zijn beperkingen enerzijds door het laadvermogen van het voertuig dat bepaald wordt door de inwendige omvormer en anderzijds door de capaciteit van een laadpunt. De capaciteit van een laadpunt is in de praktijk aanzienlijk lager dan in theorie omdat een laadpunt ten eerste niet 24 uur per dag aan het laden is en ten tweede omdat een laadpunt vaak onnodig bezet is door een reeds opgeladen voertuig. Door middel van deze richtlijn wordt het type laadpunt afgestemd op het gebruik en worden onder andere kosten bespaart.

METHODS

Voor dit onderzoek zijn verschillende methoden gebruikt en gecombineerd. Figuur 1 geeft een overzicht van de methoden en de combinaties

Multi-objective optimisation

Multi-objective optimisation maakt een afweging tussen meerdere divergerende doelstelling waardoor een set van oplossingen verkregen wordt. Het doel van multi-objective-optimisation is niet om voor een enkele doelstelling de beste oplossing te vinden maar om een compromis oplossing te vinden voor alle doelstellingen (Deb, 2005).

GIS

Geografische informatie systemen worden gebruikt om ruimtelijke data te verzamelen, analyseren, aan te passen of te presenteren. GIS is een operationeel en ondersteunend informatiesysteem waarmee gegevens aan een specifieke plaats of gebied gekoppeld kunnen worden. Door middel van GIS kunnen onder andere kaarten, grafieken en tabellen gecreëerd worden om data weer te geven.

Agent-based modelling

Agent-based modelling is een simulatie techniek voor het modelleren van complexe systemen. Een model gebaseerd op agents heeft doorgaans drie elementen: een set van agents met een bepaald gedrag, een set van onderlinge relaties en verhoudingen en methoden voor interacties tussen de agents en hun omgeving (Macal, 2010). De voornaamste voordelen van agent-based modelling is dat het in een natuurlijke beschrijving van een systeem voorziet, emergentie registreert en een flexible systeem is (Bonabeau, 2002).

Scenario analyse

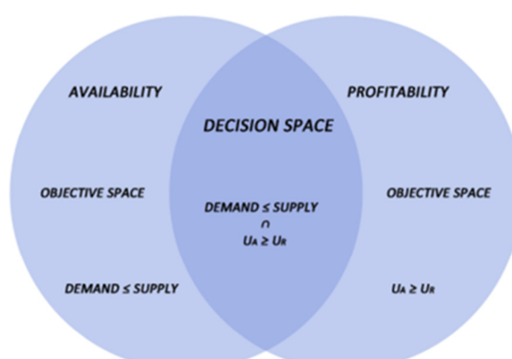
Het gebruik van scenario's stimuleert strategisch denken en het resulteert in een beter begrip van toekomstige mogelijkheden (Amer, 2012). Scenario's kunnen omschreven worden als: een set van hypothetische gebeurtenissen in de toekomst om de causaliteit van deze gebeurtenissen en de daarbij horende besluiten te verhelderen (Kahn, 2000). In feite zijn scenario's beschrijvingen van de toekomst die niet zozeer de toekomst voorspellen maar een plausibele toekomst schetsen.

Agent-based modelling en GIS zijn voor dit onderzoek gecombineerd om het locatie toewijzingsmodel voor publieke laadpunten te ontwikkelen. Door middel van multi-objective optimisation is de beslissingsruimte van het model bepaald.

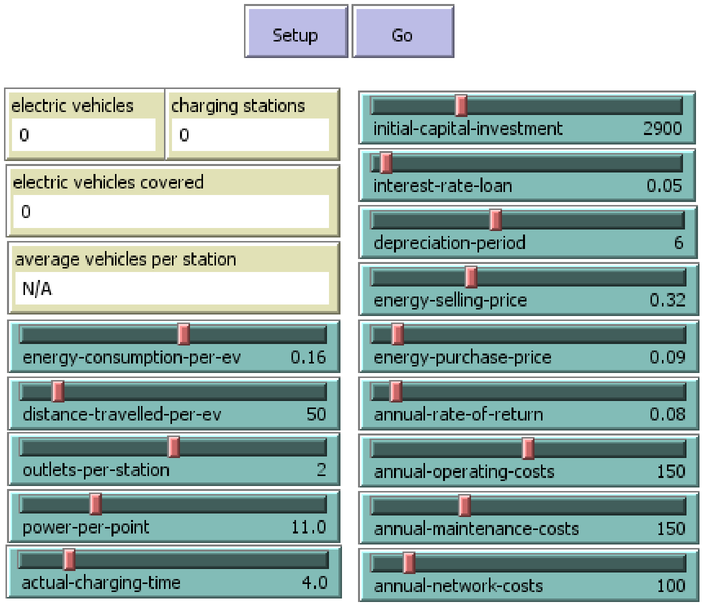
DOELSTELLINGEN EN VARIABELEN

Om de beslissingsruimte van het model te bepalen zijn twee doelstellingen gebruik; beschikbaarheid en winstgevendheid. Deze doelstellingen zijn divergerend omdat een hoge beschikbaarheid ten koste gaat van de winstgevendheid en vice versa. Figuur 2 illustreert hoe de doelstellingen samen de beslissingsruimte voor het model vormen.

DESIGN OF THE MODEL



Het model zelf is ontworpen met het software programma Netlogo. Netlogo is een relatief eenvoudig programma maar is geschikt voor het modelleren van complexe systemen. Door middel van een setup knop wordt een kaart van de gemeente Eindhoven met daarop een verdeling van elektrische voertuigen geladen. Deze verdeling van voertuigen is gebaseerd op de activiteiten wonen, werken en bezoeken van de eigenaren van de voertuigen. Per buurt zijn de voertuigen verdeeld waarbij rekening is gehouden met het verloop van elektrische voertuigen gedurende een dag. Met de go knop wordt een simulatie gestart waarbij het resultaat afhangt van de ingestelde waarden voor de variabelen die de beslissingsruimte bepalen. Voor dit onderzoek is gebruik gemaakt van een basis scenario waarmee de waarden voor de variabelen bepaald zijn. De interface met alle variabelen, is weergegeven in figuur 3.



Figuur 3: Interface van het model

CONCLUSIE

In dit onderzoek zijn in totaal 120 simulaties uitgevoerd. Iedere simulatie resulteert in een oplossing voor het probleem en door middel van verschillende criteria kan uiteindelijk de beste oplossing gevonden worden. De toegepaste criteria zijn: maximaal faciliteren, maximale winstgevendheid, maximale beschikbaarheid en een minimaal aantal laadpunten. In tabel 1 zijn de oplossingen per criterium weergegeven.

	Maximal facilitation	Maximal profitability	Maximal availability	Minimal charging stations
Charging stations	724	687	741	687
Ev's serviced	1.995	1.963	1.974	1.963
EV's/station	2,756	2,857	2,664	2,857

Tabel 11: Oplossing volgens de criteria

Gemeenten kunnen deze oplossingen gebruiken om vervolgens om straatniveau de exacte locaties voor de laadpunten te bepalen.

AANBEVELINGEN

Het model zou nog verder verfijnd kunnen worden door in GIS meer details zoals stratenpatronen en dergelijke toe te voegen. Verder zou gemeentelijk beleid toegevoegd kunnen worden om zodat op straatniveau een precieze locatie aangewezen kan worden. Bovendien blijft het van uiterst belang om de ontwikkelingen op het gebied van elektrisch rijden nauwkeurig te monitoren omdat het een de ontwikkelingen zich snel opvolgen en de gevolgen groot kunnen zijn als hier niet tijdig op in wordt gespeeld. Vooralsnog zijn de vooruitzichten voor elektrisch vervoer positief en wellicht zijn de elektrisch voertuigen in 2020 regel in plaats van uitzondering.

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